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BRITISH JOURNAL OF ANAESTHESIA

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EDITORIAL

THE ANAESTHETIST AND ADVANCES IN RESPIRATORY PHYSIOLOGY

DEVELOPMENT in any of the specialties of medicine is seldom achieved without a struggle and if recently the contents of our Journal have been a little hard to digest, it is to be hoped that this is but a sign of progress. During the last few years considerable strides have taken place in applied respiratory physiology which cannot fail to have an impact on the practice of anaesthesia, and it is likely, as can be deduced from a perusal of this issue of the Journal, that they will make possible a better understanding of processes underlying technique.

It may be that we shall come to understand something more than we do at present of what lies behind that nebulous quantity "the skill of the anaesthetist" for the anaesthetist has for a long time relied almost entirely upon his unaided senses. He knows, from practice often repeated in the healthy subject, that his simple guides are sufficient, but what normal range is in terms of measured parameters, or how far he can deviate from the limits in the sick patient without having a serious effect, is uncertain. It is fortunate that there are anaesthetists who have taken a special interest and have laboured to bring the knowledge of the respiratory physiologist within our grasp.

On too many occasions anaesthetists have argued about the probable state of carbon dioxide in the alveoli without any measurements being made. Assumptions based on other false assumptions can lead the uncritical directly away from the truth. Conceptions can be born which should have been strangled at the outset and anaesthetic practices which are undesirably introduced and perpetuated.

It cannot be denied, for example, that it would be an advantage for the anaesthetist to be able to measure tidal volume routinely without disturbing the patient. The results of such measurements would be useful at all times, especially during artificial respiration and in the recovery period while the effects of relaxant drugs are being reversed. Respiratory physiologists make such measurements often and with relative ease, anaesthetists rarely because they lack suitable equipment. The equipment of the physiologist often requires frequent checking, and the final results may have to be calculated from various forms of trace on a recorder. Stimulation of those who design instruments to plan apparatus which can be used in the operating theatre with speed and accuracy, must come from us. Provision of such instruments for anaesthetists may improve their art by the simple instillation of a little truth in place of something far less definite.

It seems appropriate at the present time to check the use of ambiguous terms, particularly those employed in respiratory phenomena. We speak of "controlled respiration" when we mean simply and solely forcing gases into the respiratory tract intermittently. When this is done by hand the inflations might be anything but controlled! Has anyone ever defined what is meant by "bucking", and is it possible for a patient to have "hiccough" with a tube in the larynx? Those who use the term "quiet breathing" may mean breathing without audible sound to an observer standing near; that there are no abnormal sounds such as stertor; that the breathing is shallow, or that it is the normal breathing at rest! Care in the use of words may almost be as important as the choice and accurate designing of apparatus.

The use of symbols to distinguish the various measurable activities in respiratory physiology was described in a previous issue of the Journal (*Brit. J. Anaesth.*, 1958, **30**, 202). Many will be dismayed by these and consider that they make articles more difficult and unattractive to read. However, there is no denying that they are extremely useful in the various mathematical calculations which must attend respiratory physiology. Their use in the Journal will be, for the most part, limited to this essential purpose.

Brit. J. Anaesth. (1958), **30**, 254

RESPIRATORY MEASUREMENTS IN THE PRESENCE OF NITROUS OXIDE

Storage of Gas Samples and Chemical Methods of Analysis

BY

J. F. NUNN

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QUANTITATIVE analysis of respiratory function during inhalational anaesthesia has lagged many years behind the collection of comparable data in the conscious subject. In part, this has been due to the presence of anaesthetic gases; nitrous oxide in particular has physical properties which interfere with a large number of conventional analytical methods. Difficulties arise partly from its high solubility in water and oil and partly from the remarkable resemblance between the other physical properties of nitrous oxide and those of carbon dioxide (table I).

A number of workers have deliberately avoided the use of inhalational agents and have thereby been able to use standard methods of analysis during anaesthesia. Dependence on intravenous agents alone for prolonged anaesthesia presents difficulties and the great majority of anaesthetists would prefer to be able to use nitrous oxide. In addition it is often an advantage to relate the data to customary anaesthetic practice. Thus, it is desirable to define the errors which may be caused by nitrous oxide and where possible to adapt techniques to eliminate them.

This paper is based on results obtained during the investigation of certain methods for analyzing respiratory gas mixtures collected from anaesthetized patients. The work was started in the

TABLE I

Physical properties of nitrous oxide and other gases.

	Nitrous oxide	Carbon dioxide	Oxygen	Nitrogen	Air
Molecular weight	44.013	44.007	32.000	28.016	
Normal mole volume (litres N.T.P.)	22.25	22.25	22.4	22.4	
B.P. (°C)	−89.5	−78.5	−183	−196	
Vapour pressure at 20°C (atmospheres)	54.0	56.8	—	—	
Solubility in oil at 37–40°C (Bunsen's coeff.)	1.40*	0.876†	0.12†	0.067‡	
Solubility in water at 20°C (Bunsen's coeff.)	0.63	0.878	0.031	0.0164	
Viscosity at 20°C (micropoises)	146	146	200	174	181
Thermal conductivity at 0°C (joules/sec/cm^3 × 10^4/°C)	1.51	1.45	2.44	2.43	2.41
Specific heat at constant pressure (joules/g/°C)	0.892	0.898	—	1.030	1.012
Velocity of sound (metres/sec at 0°C)	258	260.3	314.84	333.64	331.46
Refractive index for Sodium D line reduced to 0°C and 760 mm Hg	1.000,515	1.000,450	1.000,272	1.000,297	1.000,292

* The solubility of nitrous oxide in oil is taken from Minnitt and Gillies (1948).
† Solubility in cotton seed oil, from Schaffer and Haller (1943).
‡ Solubility in olive oil, from Vibrans (1935).
Other data are from Kaye and Laby (1956).

Department of Medicine, University of Birmingham, and completed in the Research Department of Anaesthetics of the Royal College of Surgeons. It was necessary to determine the behaviour of nitrous oxide in contact with various reagents and materials for which the relevant data could not be obtained from previously published work.

METHODS

Solubility of nitrous oxide in certain reagents.

Chemical methods of analysis of gas mixtures employ solutions of sodium or potassium hydroxide to absorb carbon dioxide, and use powerful reducing substances to combine with oxygen. A serious error would be introduced if the diluent gas were appreciably soluble in these reagents. Most methods require an acid rinsing solution in which the diluent gas should also have a low solubility.

The solubility of nitrous oxide was determined in various strengths of sodium hydroxide, saturated potassium and lithium hydroxide, and in the acid rinsing solution used in Scholander's method (1947) of gas analysis. Saturated sodium chloride solution was examined for any "salting out" properties which might reduce the solubility of nitrous oxide. A single determination was made of the solubility of cyclopropane in 25 per cent sodium hydroxide.

Qualitative estimates of solubility were made by replacing the CO_2 absorbent of the Haldane (1920) apparatus with the reagent under investigation and noting whether there was any loss of volume when nitrous oxide was repeatedly passed into the solution as in a routine Haldane analysis (Prime, 1950). Alternatively the acid rinsing solution of the Scholander apparatus was replaced by reagent and a sample of nitrous oxide drawn into the chamber. Solution was indicated by a persistent descent of the indicator droplet.

Quantitative estimates were made by saturating reagents with nitrous oxide and extracting the gas which had dissolved in them with the manometric Van Slyke apparatus (Van Slyke and Neill, 1924).

Saturation was effected by bubbling N_2O through the various reagents in a tonometer for at least one hour, by which time other dissolved gases would have been expelled. One millilitre of the reagent was then transferred anaerobically with an Ostwald pipette to the chamber of a Van Slyke manometric apparatus which had previously been rinsed with the reagent and thoroughly gas-freed. Solution of the gas had taken place at a temperature which was adjusted as closely as possible to the temperature of the water jacket of the Van Slyke apparatus. The dissolved gas was then extracted and its pressure measured at a gas volume of 2 ml (p_1). The gas then was expelled without loss of solution and a second pressure reading also taken with the meniscus at the 2 ml mark (p_2). The solution was then extracted at vacuum repeatedly and the gas (if any) expelled without loss of solution until the reading at the 2 ml mark was constant (p_3). The difference between p_2 and p_3 was small and represented the pressure of the gas partitioned in the sample after the normal procedure of extraction. Finally the apparatus was washed with distilled water and the pressure measured at the 2 ml mark over 1 ml of gas-free distilled water (p_4).

Solubility is reported as the Ostwald coefficient, which is defined as the volume of gas which dissolves in unit volume of solvent measured under the conditions of temperature and partial pressure at which solution takes place. The Ostwald coefficient varies with temperature, usually falling to zero at the boiling point of the solvent.

Calculation. The volume of gas dissolved in 1 ml of the solvent (measured at standard temperature and pressure) is given by:

$$V_{STPD}=\lambda \times \frac{273}{T} \times \frac{BP-VP}{760} \quad \text{.....(i)}$$

where λ is the Ostwald solubility coefficient;
T is the temperature (°A) at which solution occurred;
BP is the barometric pressure (mm Hg).
VP is the vapour pressure of the solvent (mm Hg).

Van Slyke's equation for dissolved gases in 1 ml of solvent is:

$$V_{STPD}=\frac{P \times 273 \times i \times a}{760 \times T}\left(1+\frac{\lambda}{49}\right) \quad \text{.....(ii)}$$

where P is the partial pressure of the extracted gas which equals p_1-p_2;
i is the correction for redissolved gas during adjustment of the volume. The error caused by this is small and i is taken as 1.014 the value for CO_2);
a is the volume at which the partial pressure of the extracted gas is measured (2 ml);
T is the temperature at which extraction of the dissolved gas takes place (°A).

Using the analytical procedure described, $\left(1+\frac{\lambda}{49}\right)$ is the correction for unextracted gas remaining partitioned in the solvent after shaking the solution at reduced pressure for 3 minutes. In the present study it would be of the order of 1.01 or less.

If solution and extraction take place at the same temperature the right hand sides of equations (i) and (ii) may be equated. Clearing and solving for λ it may be shown that:

$$\lambda=\frac{\frac{1}{\frac{BP-VP}{P \times i \times a}}}{-\frac{1}{49}} \quad \text{.....(iii)}$$

The vapour pressure of the solvent was determined by comparing the final reading after repeated extraction of gas (p_3), with a similar reading obtained with distilled water (p_4).

$$VP_{\text{solvent}} = p_3 - p_4 + VP_{\text{water}}$$

The vapour pressure of water was obtained from tables. The stronger solutions of sodium hydroxide and the mixture of glycerine and sodium chloride were too viscous to be easily stirred by the bubbles of gas passed through the solutions during saturation. It is therefore possible that saturation may not have been complete and the reported solubility would be too low.

Loss of gas through joints in glass tubing.

Certain forms of apparatus for the chemical analysis of gas mixtures incorporate rubber or plastic joints between separate glass units. If the diluent gas (present in high concentration) could easily pass through these joints it would cause a large *apparent* loss of a gas in low concentration which was undergoing chemical absorption. Flexible joints were made by interposing rubber or polyvinyl chloride tubing between lengths of capillary glass tubing. The ends of the glass tubing were 3 mm apart and its outside diameter was 6 mm, exposing a surface area of approximately 57 sq.mm. Oxygen, carbon dioxide and nitrous oxide were passed down the tube in successive experiments and one end was closed with a glass tap when flushing was completed. The other end was then sealed with a bead of mercury, whose movement indicated the net loss of gas through the joint. No correction was made for changes in ambient temperature and pressure.

Loss of gas through thin sheets of rubber and certain plastics.

The materials investigated—latex, polyethylene, polyvinyl chloride, nylon and polyethylene terephthalate ("terylene")—were obtained in tubular form and sealed at one end of a length of about 20 cm. This formed a bag in which gas could be retained for any required time, and then passed into a mercury-filled burette for measurement of volume. This was carried out at a pressure of 5 cm water below atmospheric, since it had been found that the pressure-volume relations of the bags were such that, at that pressure, gas volumes could be measured with the minimum error (less than 0.25 ml).

Oxygen, carbon dioxide and nitrous oxide were introduced successively into each bag (without a significant rise of pressure) and measured at intervals over periods of 20 to 30 minutes, depending on the rate of loss of the gas. The thickness of the walls of the bag was determined with a micrometer. No correction was made for changes in ambient temperature or pressure during the experiments which were conducted at 18–20°C.

The results are presented as the loss in ml/min/sq.m/atmosphere pressure difference across the membrane. Assuming that the loss is inversely proportional to the thickness of the wall, the results are also presented corrected to a standard thickness of 100μ (0.1 mm).

Loss of gas through soap films.

We were at one time interested in a method of collection of gas samples at a pressure close to ambient, which which would permit measurement of the volume of the sample and also storage of the sample for a few minutes prior to analysis. It appeared that collection in a graduated glass tube sealed with a soap film would be a solution to this problem, provided that there was no appreciable diffusion of gases across the film.

Samples of oxygen, nitrogen, carbon dioxide and nitrous oxide were introduced through the tap of a 25 ml burette which had been wetted with a soap solution. A single film of area approximately 0.5 sq.cm was allowed to seal the sample from the surrounding air. The outside of the film was flushed with air at a flow rate of 200 ml per min and changes in volume were measured directly by movement of the film. A control burette containing air on both sides of a soap film was placed alongside the first burette to detect any change in ambient temperature and pressure.

Loss of gas from standard items of respiratory apparatus.

Fifty litres of nitrous oxide were introduced into a 60 litre Douglas bag through a dry gas meter. After a period of 8 hours the bag was emptied through the same gas meter and the volume noted. Control measurements were made with air. A closed system consisting of a rubber bellows and a spirometer (Nunn, 1956) was filled with nitrous oxide. The bellows were alternately compressed and expanded to pass 500 ml of gas in and out of the spirometer at a frequency of 16 times a minute. Control observations were made

with the same excursion of the bellows after filling the system with air.

RESULTS

Solubility of nitrous oxide in reagents.

Nitrous oxide was found to be appreciably soluble in all the reagents studied except strong solutions of sodium hydroxide (table II and fig. 1). The solubility of cyclopropane in 25 per cent sodium hydroxide was low but significant in volumetric analysis. Saturated sodium hydroxide was found to have a very low vapour pressure and a viscosity sufficiently high to interfere with normal laboratory methods of handling solutions. Further difficulties arose from the insolubility in saturated caustic soda of the sodium carbonate resulting from the absorption of CO_2 and from the tendency for debris to float on top of the solution and so interfere with reading the level reached by the meniscus.

The hydroxides of the other alkali metals—lithium and potassium—were less viscous, but dissolved more nitrous oxide. In the case of lithium hydroxide, it is probable that this was in part due to the low solubility of the alkali in water.

It was apparent that nitrous oxide was freely soluble in Scholander acid rinsing solution (table II) and that the "salting-out" properties of sodium chloride would have been of no value in preparing a solution in which the gas would not dissolve.

Blank analyses with 100 per cent nitrous oxide in an all-glass Haldane apparatus showed that there was an appreciable loss of the gas into solutions of sodium hydroxide weaker than 70 per cent (table III). In view of the small difference

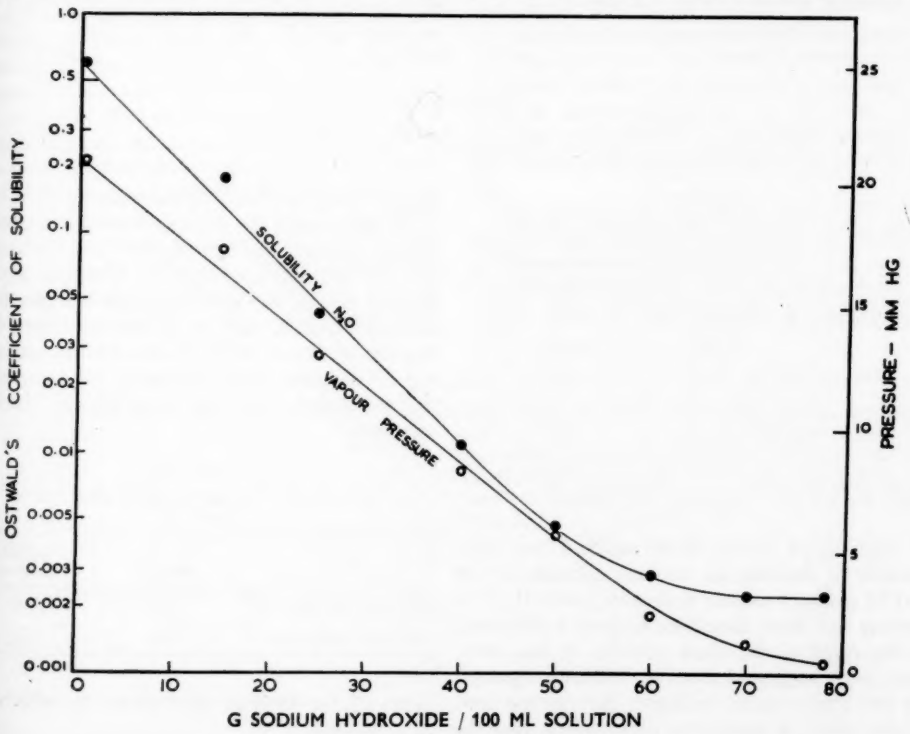

FIG. 1

The solubility of nitrous oxide in various concentrations of sodium hydroxide shown as a semi-log plot. The vapour pressure is also indicated but as a linear plot.

TABLE II

Solubility of nitrous oxide and cyclopropane in certain reagents.

	Ostwald solubility coefficient	Vapour pressure (mm Hg)	Temperature (°C)
NITROUS OXIDE			
Water	0.540	21.0	23.0
Sodium hydroxide 15%	0.179	17.3	23.5
25%	0.0434	13.0	23.0
40%	0.0109	8.2	23.0
50%	0.00463	5.9	23.0
60%	0.00269	2.3	23.0
70%	0.00224	1.4	23.0
78%	0.00224	0.3	23.0
Potassium hydroxide 100%	0.00433	0.6	23.0
Lithium hydroxide (saturated) 22.7%	0.112	18.3	23.0
Scholander acid rinse	0.323	13.5	18.0
Saturated sodium chloride solution	0.150	13.7	18.4
Equal parts: glycerine and saturated sodium chloride solution	0.182	11.0	20.0
CYCLOPROPANE			
Sodium hydroxide 25%	0.0114	13.0	23.0

TABLE III

Loss of nitrous oxide in 10 ml all-glass Haldane.

Reagent	Per cent sampled volume lost
Sodium hydroxide 60%	0.21
65%	0.08
saturated (19°C) 72%	0.02
Pyrogallol in saturated sodium hydroxide	0.05

Values are the mean of 5 experiments in each of which the gas was passed into the reagent 10 times.

in solubility of nitrous oxide which it has been possible to demonstrate between solutions of 60 and 70 per cent sodium hydroxide (table II), it is striking that there should be so great a difference in the result of the blank analyses. It has, however, been suggested that the solubility reported for the more viscous solutions may be too low. Furthermore, it should be remembered that the loss of only 0.01 ml represents 0.1 per cent of a 10 ml sample, and this would constitute a considerable error in the Haldane technique.

Loss of gas from joints in glass tubing.

An appreciable loss of nitrous oxide and carbon dioxide occurs through rubber and polyvinyl chloride connections (table IV). The loss during the first minute was generally slightly higher than the mean over 10 minutes. It may be shown that the loss of nitrous oxide from a mixture containing 70 per cent of the gas would be appreciable during analysis with the conventional Haldane apparatus.

TABLE IV

Loss of gas through joints in glass tubing (cu.mm/min)

	Rubber	Polyvinyl chloride
Carbon dioxide lost	0.23	0.91
Nitrous oxide lost	1.2	2.0

Loss of gas through thin sheets of rubber and plastics.

No decrease in volume was detected when the bags contained oxygen and were surrounded by an atmosphere of air. It will be seen from table

V that the loss of nitrous oxide was always rather more than that of carbon dioxide but considerably less through nylon and terylene than through latex, polyvinyl chloride or polyethylene. The sample of nylon was much more pliable than terylene of comparable thickness.

Gas losses were slightly greater than average in the first few minutes, but thereafter the loss became constant.

Loss of gas through soap films.

Nitrous oxide and carbon dioxide passed through the soap film in the burette so rapidly that the movement of the film caused some difficulty in reading the volume (fig. 2). Oxygen diffused out more slowly and in the case of nitrogen the gas retained behind the film actually increased in volume. This was presumably due to the greater solubility of oxygen causing this gas to diffuse in from the air more rapidly than the nitrogen diffused out. The partial pressure gradient of the two gases would be equal and opposite across the soap film, and the difference in density of the two gases would probably have negligible effect upon the rate of diffusion, since this would be inversely proportional to the square root of the density (Graham's law). In the case of nitrous oxide and carbon dioxide it is certain that both oxygen and nitrogen would have diffused inwards while the nitrous oxide or the carbon dioxide were diffusing outwards, but the inflow of the less soluble gases would have been masked by the rapid outflow of the more soluble gases. It is of interest that the comparative rate of outflow of the gases is closely related to their solubility in water. The movement of the soap film separating nitrous oxide and carbon dioxide from air was slower when only a few millilitres remained in the burette. This presumably indicated that appreciable quantities of nitrogen and oxygen had passed through the film and so reduced the partial pressure gradients across the interface. At no time did the control volume change by more than 0.05 ml in 50 ml.

Loss of gas from standard items of respiratory equipment.

The loss of nitrous oxide from the 60 litre Douglas bag amounted to 2,500 ml in 8 hours, or a mean figure of approximately 5.2 ml per minute. A control experiment with air showed an increase of 250 ml in 8 hours. This was presumably due to changes in the ambient temperature and pressure. The partial pressure gradient of nitrous oxide across the walls of the bag was close to 1 atmosphere, but the bag was at the optimum condition for retention of gas as there was a maximum volume of gas for the area of the bag.

The loss from the spirometer was small. There was no appreciable difference in the excursion of the spirometer between nitrous oxide and air. There was a total loss of nitrous oxide from the system equal to approximately 3 ml/min. It is

TABLE V

Loss of carbon dioxide and nitrous oxide through sheets of rubber and certain plastics.

Material		Loss (ml/min/m²/ atmosphere pressure difference)	Loss (ml/min/m²/ 100μ/atmosphere pressure difference)
Latex 330μ	CO_2	28.6	94.0
	N_2O	31.7	104.5
Polyvinyl-chloride (P.V.C.) 150μ	CO_2	8.33	12.5
	N_2O	14.2	21.3
Polyethylene 43μ	CO_2	10.5	4.51
	N_2O	22.9	9.85
Polyethylene terephthalate (terylene) 12μ	CO_2	1.0	0.12
	N_2O	3.7	0.44
Nylon 18μ	CO_2	0.65	0.12
	N_2O	1.1	0.20

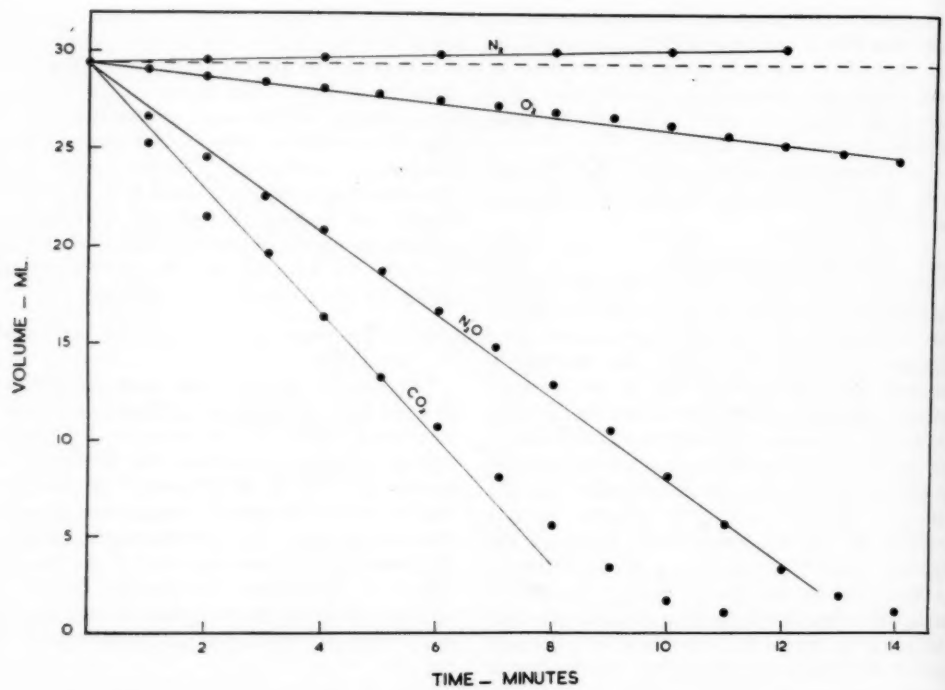

FIG. 2

The changes in volume occurring when certain gases are separated from room air by a soap film of area approximately 0.5 sq.cm.

possible that part of this took place through the metre length of corrugated rubber tubing which connected the spirometer to the bellows.

DISCUSSION

Chemical methods of gas analysis.

Chemical methods of gas analysis are dependent upon the measurement of the volume of a gas sample before and after the chemical absorption of a particular constituent. No gas must be lost before the initial measurement and at each absorption only the required gas must be taken up. Compensation must be made for changes in temperature and pressure during analysis and all measurements must be made with the gas in contact with solutions of the same vapour pressure. In the case of Haldane's method, all measurements are made with the bulk of the gas in contact with the acid rinse, while in Scholander's method all three reagents used are designed to have the same vapour pressure.

With nitrous oxide present in the diluent gas three problems arise. Firstly, the gas is soluble in the usual reagents for the removal of carbon dioxide and oxygen. However, Prime (1950) showed that nitrous oxide was almost insoluble in *saturated* sodium hydroxide and we have been able to confirm this. If saturated sodium hydroxide is the only carbon dioxide absorbent which can be used, the very low vapour pressure of this solution presents the second difficulty. It would appear to preclude its use in Scholander's apparatus, as we have been unable to devise an acid-rinse solution in which nitrous oxide is insoluble and which has a vapour pressure as low as that of saturated sodium hydroxide. Even concentrated sulphuric acid will take up the gas. Fortunately the vapour pressure of the absorbent

solutions is of little importance in Haldane's method as only a very small part of the gas is in contact with the absorbents when the gas volume is being measured.

The third difficulty in chemical analysis in the presence of nitrous oxide arises from incidental loss of gas through the walls of the apparatus. Harbord (personal communication) and the author were both unable to obtain constant readings with 100 per cent nitrous oxide during blank analyses in an ordinary Haldane's apparatus with saturated sodium hydroxide in the absorption chamber. By exclusion of other factors it became evident that, during transfer of gas to the absorption vessel, nitrous oxide was being lost through the rubber joints in the glass tubing. As the loss shown in table IV was sufficient to account for the loss which was found, an all-glass Haldane apparatus was made with a ball-and-socket joint in place of flexible connections (fig. 3). It later transpired that Prime (personal communication) had used an all-glass apparatus in his original work without realizing that this was, in fact, essential.

The all-glass Haldane apparatus used with saturated sodium hydroxide requires considerable skill in operation, but is satisfactory for routine use in an anaesthetic laboratory investigating respiratory problems. Certain details are important. Saturated sodium hydroxide solution is difficult to use because of its high viscosity and the distortion of the meniscus by floating debris. It was hoped that potassium or lithium hydroxide might prove suitable, but in each case the solubility of the gas was higher. The alkali tends to absorb moisture if exposed to the air and should therefore be discarded and replaced each time it is used. We have found it convenient to store the solution in a polyethylene bottle in contact with excess solid sodium hydroxide. The absorption chamber should be washed with distilled water and drained after use. The saturated alkali is dangerous to handle but should not etch the glass of the absorption chamber if it is washed out after use. Very large errors will occur if the acid rinse dries from the burette and it is important to check on the amount present. The acid rinse will take up some nitrous oxide and it is necessary to perform a blank analysis on the gas sample to saturate the acid rinse.

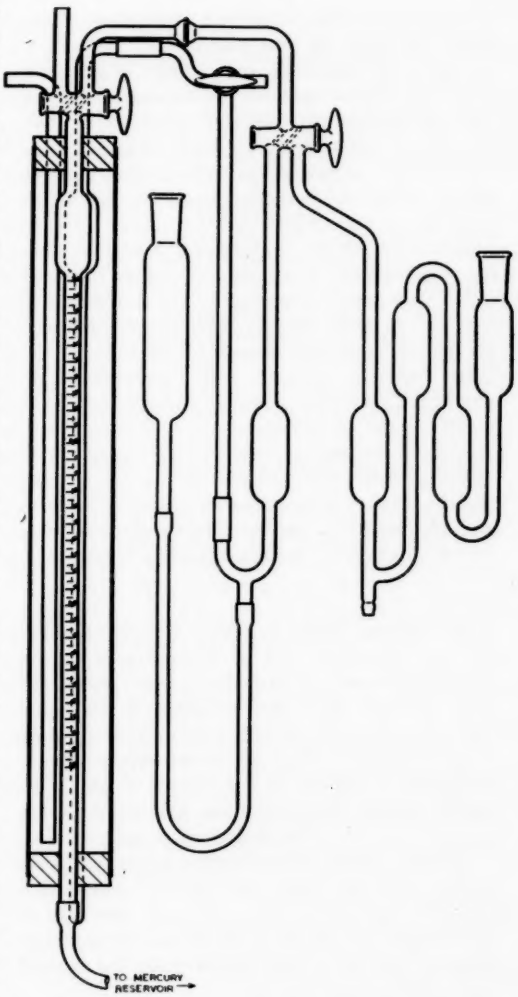

FIG. 3

Modification of Haldane's apparatus for use in the presence of gases with an appreciable rate of diffusion through rubber or polyvinyl chloride connections.

The use of the method for the determination of the oxygen concentration of gas samples presents difficulties which have not been satisfactorily solved. It is normal practice to fill the oxygen absorption chamber with glass rods to increase the

surface area and so accelerate absorption. Pyrogallol dissolved in saturated caustic soda does not wet glass uniformly and bubbles of gas tend to be left behind between the rods. If, however, the rods are omitted the time required for full absorption of oxygen is very long indeed.

Chemical analysis of gas mixtures containing nitrous oxide has been developed for the determination of the carbon dioxide output and the measurement of the physiological deadspace during anaesthesia. Furthermore, since Ramwell (1957) has drawn attention to collision broadening as an error in gas analysis by infrared absorption, it appears desirable to be able to calibrate infrared analyzers with carbon dioxide mixtures dispersed in a diluent gas of composition similar to the anaesthetic mixture. It is our practice to fill calibrating cylinders with mixtures of carbon dioxide, nitrous oxide and oxygen, obtaining the desired proportions by pressure dilution, and checking the carbon dioxide concentration at intervals with the modified Haldane's apparatus.

Storage of gas samples.

We have no reason to believe that there would be any appreciable loss of nitrous oxide during storage in a mercury sealed tonometer or an all-glass syringe. We were, however, at one time interested in the possibility of collecting small samples of expired gas in vessels which offered negligible resistance to the inflow of gas. This led to the investigation of the passage of certain gases across thin films and membranes.

It soon became apparent that it was not practicable to keep gases of different composition separated by a soap film, although the ease of measuring the volume retained and the high frequency response of the system made the method particularly attractive.

The different rates of diffusion of gases of different solubility make it possible to "dialyse" the more soluble gases out of a gas mixture. There are, however, considerable practical difficulties in the use of this principle for volumetric analysis. The movement of a soap film would represent the algebraic sum of the transfer of all gases present on both sides of the film, and thus the determination of the original concentration of one component would present considerable difficulty.

The loss of gas through rubber and plastic membranes is much slower but still appreciable. Assuming the loss to be proportional to the partial pressure gradient across the membrane, it is possible with the data of table V to calculate the changes which would take place in various gas mixtures on storage. For a mixture of carbon dioxide and oxygen, there would be a steady fall in the carbon dioxide concentration, depending on the material and the ratio of the area of the bag to the volume of the gas sample. In the case of expired gas during nitrous oxide anaesthesia the changes would be different as both carbon dioxide and nitrous oxide would be lost in appreciable quantities. It so happens that the different rates of diffusion of these gases, and the partial pressures in which they are likely to exist under these circumstances would combine to keep the carbon dioxide concentration surprisingly constant. These points may best be illustrated by examples:

Latex bag of area 126 *sq.cm and thickness* 330μ.

Initial composition	Composition after 5 min
CO_2 5.00% O_2 95.00% (Total volume 50 ml)	CO_2 4.84% O_2 95.16% (Total volume 49.91 ml)
CO_2 5.00% N_2O 70.00% O_2 25.00% (Total volume 50 ml)	CO_2 4.98% N_2O 69.25% O_2 25.77% (Total volume 48.51 ml)

The use of nylon for gas storage would reduce the loss of gas considerably although it should not exceed a thickness of 20μ for convenient handling. Below are given comparable figures for gas changes in a nylon bag.

Nylon bag of area 135 *sq.cm and thickness* 18μ.

Initial composition	Composition after 5 min
CO_2 5.000% O_2 95.000% (Total volume 50 ml)	CO_2 4.999% O_2 95.001% (Total volume 49.998 ml)
CO_2 5.001% N_2O 70.000% O_2 25.000% (Total volume 50 ml)	CO_2 5.001% N_2O 69.974% O_2 25.025% (Total volume 49.948 ml)

The loss of nitrous oxide from the 60 litre Douglas bag corresponds to 300 ml per hour at 1 atmosphere pressure difference across the wall of the bag. Mills (1952) and Shephard (1955) found losses of carbon dioxide from Douglas bags

of the order of 0.01 to 0.03 per cent carbon dioxide per hour from 3.5 to 4.0 per cent mixtures of carbon dioxide in air. These losses are of the same order as that found for nitrous oxide and it may be assumed that much the same relations between the two gases apply as was found for small latex bags.

In view of the high solubility of nitrous oxide in water it was surprising that the loss of gas into the water bath of a spirometer should be so low. It is apparent that in clinical spirometry no account need be taken of this loss.

SUMMARY

We have investigated certain physical properties of nitrous oxide which are of importance in the storage and chemical analysis of gas samples collected during anaesthesia. The solubility of the gas in a number of laboratory reagents has been investigated and also its rate of diffusion through soap films and thin membrances of latex and various plastics.

The application of these findings to methods of gas analysis and storage is discussed.

A modification of Haldane's apparatus is described and certain technical difficulties of the method are discussed.

ACKNOWLEDGMENTS

I wish to thank Dr. R. F. Woolmer for reading and criticizing the manuscript of this paper. I am indebted to Professor W. Melville Arnott for the facilities so generously supplied for the early part of this work which was carried out in the Department of Medicine of the University of Birmingham during the tenure of an Endowment Research Fund Fellowship. It is a pleasure to acknowledge the help and advice given to me by Mr. R. G. Mills. To Miss T. C. Guilfoyle I am grateful for much painstaking work in finding the sources of error with the modified Haldane's apparatus.

The design and construction of the modified Haldane's apparatus was carried out by Mr. R. H. Powell of Messrs. Griffin and George Ltd., Main Street, Sparkbrook, Birmingham.

REFERENCES

Haldane, J. S. (1920). *Methods of Air Analysis*, 3rd ed., p. 9. London: Charles Griffin & Co.

Kaye, G. W. C., and Laby, T. H. (1956). *Tables of Physical and Chemical Constants*, 11th ed. London: Longmans, Green and Co.

Mills, J. N. (1952). The use of the infra-red analyser in testing the properties of Douglas bags. *J. Physiol.*, **116**, 22P.

Minnitt, R. J., and Gillies, J. (1948). *Textbook of Anaesthetics*, 7th ed., p. 105. Edinburgh: Livingstone.

Nunn, J. F. (1956). A new method of spirometry applicable to routine anaesthesia. *Brit. J. Anaesth.*, **28**, 440.

Prime, F. J. (1950). Volumetric determination of ether, carbon dioxide, nitrous oxide and oxygen in anaesthetic mixtures. *Brit. J. Anaesth.*, **22**, 162.

Ramwell, P. W. (1957). The infra-red analysis of carbon dioxide during anaesthesia. *Brit. J. Anaesth.*, **29**, 156.

Schaffer, P. S., and Haller, H. S. (1943). Solubility of gases in butter oil, cotton seed oil and lard. *Oil and Soap*, **20**, 161.

Scholander, P. F. (1947). Analyser for accurate estimation of respiratory gases in one-half cubic centimetre samples. *J. biol. Chem.*, **167**, 235.

Shephard, R. J. (1955). A critical examination of the Douglas bag technique. *J. Physiol.*, **127**, 515.

Van Slyke, D. D., and Neill, J. M. (1924). The determination of gases in blood and other solutions by vacuum extraction and manometric measurement. *J. biol. Chem.*, **61**, 523.

Vibrans, F. C. (1935). Solubility of gases in edible fats and oils. *Oil and Soap*, **12**, 14.

Brit. J. Anaesth. (1958), **30**, 264

THE DRÄGER CARBON DIOXIDE ANALYZER

BY

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THERE has long been a need for a simple and portable carbon dioxide analyzer suitable for use in the operating theatre or at the bedside. The analyzer to be described* appeared to fulfil many of the requirements, and we have therefore made a critical study of its performance with special reference to its use during anaesthesia. No details of its performance have yet been published but Scurr (1956) has reported its use during anaesthesia.

DESCRIPTION

The analyzer was devised during the last war for use in submarines. It is in the form of a perspex cylinder 5 cm in diameter and 20 cm in length. The lower part rotates on the top part, thereby operating the taps which direct the gas into the various parts of the apparatus.

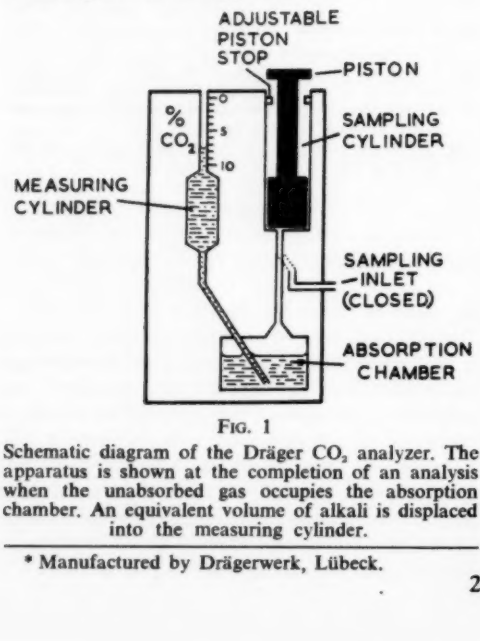

FIG. 1

Schematic diagram of the Dräger CO_2 analyzer. The apparatus is shown at the completion of an analysis when the unabsorbed gas occupies the absorption chamber. An equivalent volume of alkali is displaced into the measuring cylinder.

* Manufactured by Drägerwerk, Lübeck.

The analyzer is shown diagramatically in figure 1. Gas is drawn directly into the sampling cylinder by the piston, whose stroke is limited by an adjustable stop. This samples a predetermined volume (approximately 10 ml) which is repeatable within very narrow limits. The gas is then passed into the absorption chamber containing 25 per cent sodium hydroxide. Carbon dioxide in the sample is rapidly absorbed and a volume of alkali, approximating to the residual gas volume, is forced into the measuring cylinder which is graduated to indicate the percentage of the sample which has been absorbed. In figure 1 the analysis is completed and the alkali is partly displaced into the measuring cylinder. The piston stop is previously adjusted to give a zero reading during a blank analysis of gas which contains no carbon dioxide.

SOURCES OF ERROR

The gas analyzers of Haldane (1920) and Scholander (1947) have been carefully designed to ensure that all measurements of gas volumes are made under the same conditions of temperature and pressure and with the gas in contact with liquids of the same vapour pressure. In the Dräger analyzer, however, the conditions before and after absorption of the carbon dioxide are different. Gas is drawn into the sampling cylinder (and thereby measured) at ambient temperature and pressure. Expired gas will be saturated with water vapour at ambient temperature. In the absorption chamber the vapour pressure of the alkali is some 10 mm Hg less than that of water at room temperature and the gas volume will be further reduced by the hydrostatic pressure of the column of alkali forced into the measuring cylinder—also of the order of 10 mm Hg. If these errors are constant, compensation is possible by adjustment of the piston stop.

There are various sources of random error of which by far the most important is differences in temperature between the sampling cylinder and absorption chamber. The apparatus should always be allowed sufficient time to assume the temperature of the room in which the analysis will take place. Regional heating by sunlight or proximity to radiators will introduce a serious error, but more insidious is the heat of the operator's hand.

The error due to changing ambient temperature.

If regional heating is avoided, changing ambient temperature will affect both sampling cylinder and absorption chamber and there will be no resultant error from expansion of the gas. However, the vapour pressures of water (P_{H_2O}) and caustic soda (P_{NaOH}) will both vary with changing temperature. The volume of CO_2-free gas (V) on passing into the absorption chamber will become:

$$\frac{P_B - P_{H_2O}}{P_B - P_{NaOH}} \cdot V$$

where P_B is the barometric pressure.

This factor will vary appreciably with changes in temperature, but not to any significant degree with changes in barometric pressure over the normal range.

The error due to the hydrostatic pressure of the column of sodium hydroxide in the measuring cylinder.

The volume of CO_2-free gas will be reduced on passing into the absorption chamber by a factor dependent upon the hydrostatic pressure of the sodium hydroxide. If the vertical height of the column is h and the specific gravity of the liquid is ρ the factor will be:

$$\frac{P_B}{P_B + h \times \rho}$$

The specific gravity of 25 per cent sodium hydroxide is 1.21 and the height of the column varies with the part of the scale reached by the alkali:

$$h = (16 - 0.45 \times S) \text{ cm}$$

where S is the scale reading in percentage of CO_2.

Thus the factor for the hydrostatic pressure becomes:

$$\frac{P_B}{P_B + 1.21\ (16 - 0.45 \times S)}$$

Changes in the barometric pressure within the normal range will not affect the factor appreciably. During a blank analysis with CO_2-free gas the piston stop may be adjusted by trial and error to correct for both the hydrostatic pressure and the temperature effect. Thereafter only changes in the ambient temperature or the strength of the alkali would necessitate resetting of the piston stop.

It is clearly not feasible to reset the piston stop to compensate for the different hydrostatic pressures obtained with different concentrations of CO_2 in the sampled gas. The error from this effect is, however, proportional to the concentration of CO_2 and allowance could be made—either as a correction factor or by an adjustment of the engraved scale.

A number of experiments were carried out to determine the magnitude of these errors in practice. In addition, an assessment was made of the error due to the presence of nitrous oxide in the diluent gas. This gas is freely soluble in dilute caustic soda and we therefore explored the use of saturated alkali, in which nitrous oxide is almost insoluble.

METHOD OF ASSESSMENT

The entire apparatus was kept at a constant temperature for at least one hour before use. The analyzer was held in a retort stand and handling was avoided as far as possible. All gases were sampled from a moist 100 ml syringe, in which they were allowed to become saturated with water vapour. No samples of dry gas were analyzed, as this would require resetting of the piston stop.

Zero adjustments were made by performing a blank analysis on air which had been freed of CO_2 with soda lime and saturated with water vapour. The piston stop was adjusted by trial and error until zero readings were obtained. Calibration was carried out against five cylinders of CO_2 in nitrogen which had been analyzed by the method of Haldane.

For the studies on the effect of nitrous oxide, mixtures of CO_2 were prepared in a diluent gas of 70 per cent nitrous oxide and 30 per cent oxygen. The CO_2 concentration in these mixtures was determined by the modification of the Haldane technique described by Prime (1950).

CO_2 concentrations were determined to within 0.1 per cent and errors are expressed as a percentage of the sampled volume.

RESULTS

Setting of the piston stop for the zero reading tended to be tedious and time consuming. The setting generally gave readings within 0.1 per cent of zero for 12 hours. Thereafter the reading tended to rise by 0.2 per cent per day—possibly as a result of the alkali taking up moisture.

The effect of ambient temperature on the zero setting was studied by adjusting the piston stop for CO_2-free gas at 25°C and repeating the observations after equilibration at 13°C and 32°C.

At the low temperature the values obtained varied from 0.2 to 0.4 per cent below zero and at the high temperature from 0.2 to 0.4 per cent above zero.

The calibration against Haldane's method is shown in figure 2. The solid line indicates one-to-one correspondence, while the broken line indicates the mean of five analyses on each gas cylinder. The random error at no time exceeded 0.1 per cent. The systematic error is proportional to the concentration of CO_2 in the sample and is 0.06 per cent high for each 1 per cent of CO_2 in the sample.

Dräger analysis of CO_2 in a diluent of nitrous oxide and oxygen gave a value which was much higher than the concentration determined by the Haldane method (fig. 3). Subsequent analyses gave lower values which approached the true value in a quasi-exponential manner, as the alkali approached saturation with nitrous oxide. Nevertheless even after seven analyses the error was still appreciable at almost 1 per cent.

Immediately after eight analyses with nitrous oxide present, a series was commenced with CO_2 dispersed in nitrogen. Nitrous oxide then came out of solution giving a reading less than the true value (fig. 3).

The analyzer was then filled with saturated caustic soda (72 per cent or 18 normal). A considerable re-adjustment of the piston stop was required as the vapour pressure of saturated soda is less than 1 mm Hg. Analysis with the con-

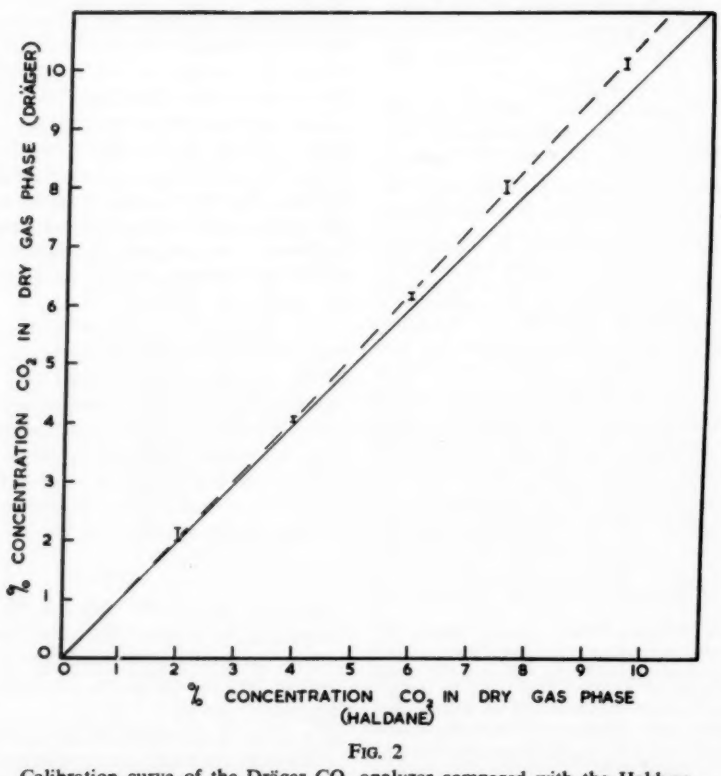

FIG. 2

Calibration curve of the Dräger CO_2 analyzer compared with the Haldane apparatus, for mixtures of carbon dioxide and nitrogen. The broken line joins the mean values obtained with five gas mixtures. The horizontal lines indicate the range of the individual readings.

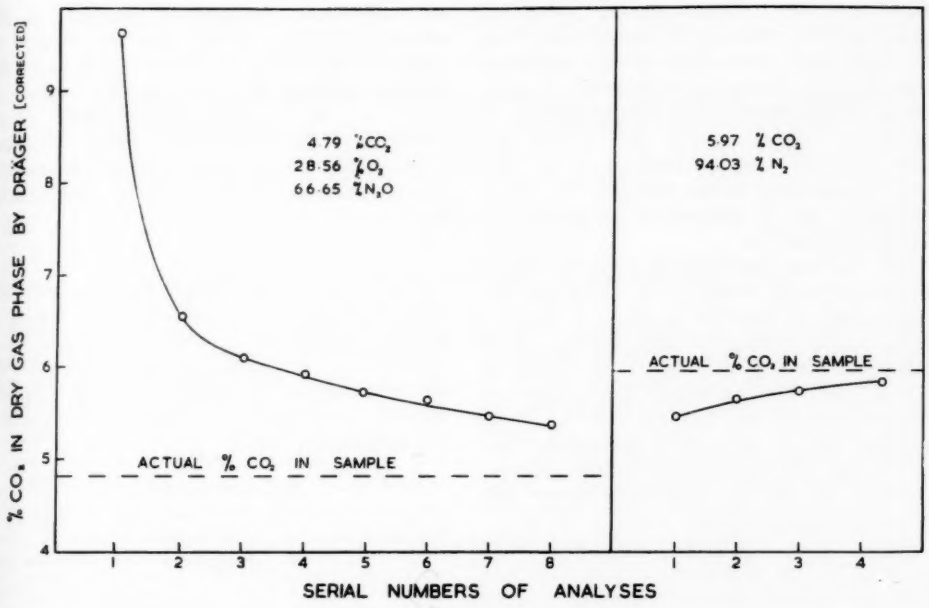
% CO₂ IN DRY GAS PHASE BY DRÄGER [CORRECTED]
4.79 % CO₂
28.56 % O₂
66.65 % N₂O
5.97 % CO₂
94.03 % N₂
ACTUAL % CO₂ IN SAMPLE
ACTUAL % CO₂ IN SAMPLE
SERIAL NUMBERS OF ANALYSES

FIG. 3

The results of a series of analyses of carbon dioxide dispersed in a nitrous oxide-oxygen mixture, followed by a second series of analyses of a mixture of carbon dioxide in nitrogen. The inset figures indicate the carbon dioxide concentration determined by the Haldane method. The results obtained by the Dräger method have been corrected according to the calibration curve (fig. 2).

centrated solution was difficult due to its high viscosity. At the completion of each analysis the solution required about 4 minutes to drain back into the absorption chamber from the measuring cylinder. Attempts to hurry the process with positive pressure introduced considerable errors which were probably due to irregular drainage.

Using the saturated alkali, six analyses were made on a mixture containing 4.79 per cent CO_2 dispersed in 70 per cent nitrous oxide and 30 per cent oxygen. The mean value obtained was 4.92 per cent (range 4.8–5.1) and this agrees closely with the calibration curve (fig. 2). Six analyses were then made on a mixture containing 9.14 per cent CO_2 in the same diluent gas. The mean value was 9.48 per cent (range 9.3–9.7) showing a deviation of 0.2 per cent from the calibration curve and a greater random error.

It was repeatedly found that when the apparatus was held in the hand, large errors became apparent and it was impossible to obtain agreement between duplicate analyses. Even with our precautions against local heating it was often found to be difficult to carry out correctly more than three analyses in succession.

CONCLUSIONS

It appears that the Dräger CO_2 analyzer has sufficient accuracy for clinical use. Its portability and ease of operation make it suitable for use in the operating theatre or at the bedside. Its apparent simplicity is, however, deceptive and attention to certain details is necessary if the results are to be of value.

Zero setting. It is advisable to check the setting of the piston stop each time the apparatus is used. This is particularly important if the ambient temperature is markedly different or if the alkali is changed.

Calibration error. Each apparatus should be checked against mixtures of known CO_2 concentrations and a note made of any significant systematic error. Calibration provides the operator with invaluable experience in the handling of the apparatus.

Saturation of samples. Samples of dry gas should be saturated before analysis. All expired gas samples can be assumed to be saturated at ambient temperature.

Local heating. It is of the greatest importance that the apparatus should be at a uniform temperature and not exposed to direct sunlight or placed near a radiator. During analysis, direct handling of the apparatus should be avoided as far as possible. We recommend that the operator should wear gloves and hold the analyzer for the minimum time. In spite of all precautions there is often a tendency for some part of the apparatus to become heated and errors may appear after three consecutive analyses.

Nitrous oxide. The presence of nitrous oxide will result in the indicated percentage of CO_2 being too high through physical solution of the diluent gas in the alkali. "Saturation" of the alkali with nitrous oxide is not a reliable method of avoiding this error and furthermore it will lead to an error if the same alkali is used for subsequent analyses on gas mixtures which do not contain nitrous oxide. Nitrous oxide is almost insoluble in saturated sodium hydroxide and this solution is suitable for the analysis of gas mixtures containing nitrous oxide. It is, however, necessary to alter the piston stop when the alkali is changed, as the vapour pressure is thereby altered. The analysis is more difficult to perform with the saturated solution and the results are slightly less accurate.

Sampling. Sampling techniques are outside the scope of this paper, but it is important to realize that the accuracy of estimation of the alveolar gas composition is generally limited by the sampling technique rather than the method of analysis. The Dräger analyzer can be used for samples collected manually by the method of Inkster and Rees (1956) or automatically by the method of Nunn and Pincock (1957). The sampling cylinder can probably be used for sampling directly although this would require some manual dexterity.

SUMMARY

The accuracy of the Dräger CO_2 analyzer has been examined. Factors affecting the setting of the zero adjustment have been investigated and the error due to nitrous oxide in the gas samples has been assessed. A method has been suggested whereby it is possible to analyze a mixture which contains nitrous oxide.

ACKNOWLEDGMENTS

I am indebted to Dr. R. F. Woolmer for his help in the preparation of this manuscript.

Messrs. Garthur Ltd. generously donated the Dräger analyzer on which this work was carried out. A new model has now been produced in which the zero setting is simplified and with some precautions against local heating.

REFERENCES

Haldane, J. S. (1920). *Methods of Air Analysis*, 3rd ed., p. 9. London: Charles Griffin & Co.

Inkster, J. S., and Rees, L. T. (1956). A simple method of carbon dioxide estimation in expired air. *Brit. J. Anaesth.*, **28**, 37.

Nunn, J. F., and Pincock, A. C. (1957). A time-phased end tidal sampler suitable for use during anaesthesia. *Brit. J. Anaesth.*, **29**, 98.

Prime, F. J. (1950). Volumetric determination of ether, carbon dioxide, nitrous oxide and oxygen in anaesthetic mixtures. *Brit. J. Anaesth.*, **22**, 162.

Scholander, P. F. (1947). Analyzer for accurate estimation of respiratory gases in one-half cubic centimetre samples. *J. biol. Chem.*, **167**, 235.

Scurr, C. F. (1956). Pulmonary ventilation and carbon dioxide levels during anaesthesia. *Brit. J. Anaesth.*, **28**, 422.

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A THEORETICAL INVESTIGATION OF OXYGEN CONCENTRATIONS IN GASES INSPIRED FROM VARIOUS SEMICLOSED ANAESTHETIC SYSTEMS

BY

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It has long been recognized that when a patient breathes a mixture of oxygen and nitrous oxide from a semiclosed system, the concentration of oxygen in the inspired gas is not necessarily equal to the concentration of oxygen in the fresh gases supplied by the anaesthetic machine. This fact has been amply demonstrated by actual measurement by Crowley, Faulconer and Lundy (1948), and by Swartz, Adriani and Mih (1953), to mention only two groups of investigators.

The theoretical approach to the problem has been less fruitful. Molyneux and Pask (1951) derived a formula for evaluation of the volume of expired gas which was returned to a to-and-fro system at each expiration, and confirmed their predictions experimentally. Their analysis has not been made use of in the present paper because it involved the assumption of an idealized respiratory pattern.

Foldes et al. (1952) discussed the administration of nitrous oxide-oxygen mixtures in *closed* systems, and deduced a formula which they claimed would predict the inhaled oxygen concentration with an error of not more than 5 per cent. Now an inert gas like nitrous oxide, which for all practical purposes is excreted entirely by the lungs, cannot be fed indefinitely into a true closed system. If it is, the reservoir bag will distend progressively, or the depth of anaesthesia will have no limit. The system is thus truly closed only as long as the patient continues to absorb nitrous oxide at the same rate as that at which it enters the system. The systems considered by Foldes et al. would therefore be more correctly described as *semiclosed*, and the formula deduced might be supposed to be applicable to a semiclosed system. But despite the claims made for it, this formula fails to take account of several important factors, and cannot be regarded as mathematically correct for either type of system.

Ruben (1953) presented an equation connecting inspired oxygen concentration, flowrates, and respiratory minute volume, and seems to have intended it to be applicable to any semiclosed system. In order to deduce this equation, however, Ruben made two important assumptions which may be restated thus:

(*a*) The concentration of oxygen in the expired gas is constant over the one-minute period studied.

(*b*) In all semiclosed systems, there is no loss of *fresh* gases from the expiratory valve at any stage of the respiratory cycle, i.e. the volume of fresh gases inspired during any one minute is equal to the volume of fresh gases entering the system from the machine in that minute.

Of these two assumptions, the first was, at best, only approximately true, and in any case cannot be applied when the system is used for long periods; and the second assumption was not proven by Ruben either for a particular system or for semiclosed systems in general. Nevertheless, Ruben's work laid the foundation for the present analysis, but his fundamental assumptions have been excluded.

Mapleson (1954) extended the theoretical analysis of Molyneux and Pask by an approach which, in certain systems, eliminated the need for postulating any particular pattern of breathing, and the present author has drawn freely upon a number of Mapleson's conceptions.

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In this paper it is intended to derive a general equation which expresses the mean concentration of oxygen in the gases inspired from any semiclosed system in terms of certain parameters, and subsequently to apply this equation to each of several systems in common use.

ASSUMPTIONS

Certain assumptions, some of which will require justification or limitation at a later stage, must be made at the outset, and these are as follows:

(1) The patient's minute volume, tidal volume, and entire respiratory pattern remain constant during the period under consideration.

(2) The gas flowing from the anaesthetic machine contains oxygen and nitrous oxide only, and is of constant composition.

(3) The patient is assumed to be saturated with nitrous oxide from the beginning of the analysis, so that no correction need be made for volume changes due to absorption of nitrous oxide or washing out of nitrogen. This may seem an unwarranted assumption, but the present analysis seeks to establish the oxygen concentrations existing after an indefinitely long period of breathing from the system, by which time the nitrogen-nitrous oxide exchange in the body may be supposed to be complete.

(4) The respiratory quotient is unity, so that whatever oxygen is absorbed during one respiratory cycle is replaced by an exactly equal volume of carbon dioxide, and no net change of volume occurs.

(5) No carbon dioxide absorber is in use. (This assumption is discussed in detail at a later stage.)

(6) No alterations in gas concentrations occur due to expired water vapour or temperature changes.

(7) The total flowrate per minute of fresh gases from the machine is not greater than the patient's respiratory minute volume.

(8) The expiratory valve opens at some point during the expiratory phase when the pressure within the system reaches a certain fixed value, and the valve then remains open until the next inspiration begins.

(9) Pressure changes within the system are sufficiently small to allow consequent volume changes to be neglected.

SYMBOLS

So far as is possible, the symbols used in this paper are those recommended by Pappenheimer (1950).

$\bar{F}_{I_n}$ = Mean fractional oxygen concentration in inspired gas at nth inspiration.
$\bar{F}_{E_n}$ = Mean fractional oxygen concentration in expired gas at nth expiration.
$F_{M_{O_2}}$ = Fractional concentration of oxygen in fresh gases from machine.
$\dot{V}_M$ = Total fresh gas flowrate from machine (litres/minute).
$\dot{V}_T$ = Patient's minute volume (litres/minute).
V_T = Patient's tidal volume (litres).
t_1 = Time from beginning of one inspiration to the end of the same inspiration (minutes).
t_2 = Time from end of one inspiration to beginning of next inspiration (minutes).
t' = Time from end of inspiration to opening of expiratory valve (minutes).
t = Time of one complete respiratory cycle ($= t_1 + t_2$) (minutes).
f = Respiratory frequency ($= 1/t$).
$P_{A_{O_2}}$ = Alveolar partial pressure of oxygen (mm Hg).
$P_{I_{O_2}}$ = Inspired partial pressure of oxygen (mm Hg).
$P_{A_{CO_2}}$ = Alveolar partial pressure of carbon dioxide (mm Hg).

DERIVATION OF A GENERAL EQUATION FOR OXYGEN CONCENTRATION IN GASES INSPIRED FROM ANY SEMICLOSED SYSTEM

The use of a semiclosed system presupposes that some rebreathing of expired gas takes place, and the degree to which this rebreathing occurs will depend upon the relationship between the patient's minute volume and the minute flowrate of fresh gases into the system.

It may therefore be postulated that the gas inspired by the patient at any one inspiration is derived from two sources: (*a*) a part consisting of fresh gases from the machine and, (*b*) a part consisting of gas which has been expired by the patient at a previous expiration.

If the system is filled with fresh gases from the machine when the first breath is taken, the oxygen concentration in the first inspiration must be equal to that in the fresh gases. All subsequent inspirations must include some expired gas, and therefore the inspired oxygen concentration may be expected to decrease progressively as breathing continues. It will first be shown that as the number of respiratory cycles becomes very large the inspired oxygen concentration tends to a certain minimum value; in other words, a steady state is reached in the system. Clearly, it is only this equilibrium

concentration of inspired oxygen which is of importance to the anaesthetist.

Suppose that at any inspiration the patient receives x litres of fresh gas from the machine and rebreathes y litres of expired gas.

Then $V_T = x + y$

The volume of oxygen inspired at the nth inspiration is $V_T \cdot F_{I_n}$, and this must be equal to the sum of the oxygen contents of x and y.

$$\therefore \quad V_T \cdot F_{I_n} = x \cdot F_{M_{O_2}} + y \cdot F_{E_{(n-z)}} \ldots\ldots (1)$$

(The concentration of oxygen in the rebreathed fraction is equal to the concentration in the $(n-z)$th expiration, where z will be unity or some greater number depending upon the system used.)

Now it has been shown that in dogs breathing air at subatmospheric pressures, the oxygen content of the arterial blood remains normal provided that the ambient atmospheric pressure is not less than 410 mm Hg (Luciani, 1911). Hence, over a wide range of inspired oxygen partial pressures, the volume of oxygen (reduced to atmospheric pressure) abstracted by the pulmonary blood flow at each respiratory cycle is constant.

$$\therefore \quad V_T(F_{I_n} - F_{E_n}) = \text{a constant}$$

Since V_T is also constant under the conditions of this analysis,

$$F_{I_n} - F_{E_n} = k \quad \text{(another constant)}$$

$$\therefore \quad F_{E_{(n-z)}} = F_{I_{(n-z)}} - k.$$

Substituting this value of $F_{E_{(n-z)}}$ in equation (1),

$$V_T \cdot F_{I_n} = x \cdot F_{M_{O_2}} + y(F_{I_{(n-z)}} - k)$$

$$\therefore \quad F_{I_n} = \frac{x}{V_T} \cdot F_{M_{O_2}} + \frac{y}{V_T}(F_{I_{(n-z)}} - k) \ldots\ldots (2)$$

Now consider the special case where $z = 1$. Put

$$\frac{x}{V_T} \cdot F_{M_{O_2}} = A, \text{ and } \frac{y}{V_T} = B.$$

Then, substituting in (2),

$$F_{I_n} = A + B(F_{I_{(n-1)}} - k)$$

But at the first inspiration, $F_{I_1} = F_{M_{O_2}}$

$$\therefore \quad F_{I_2} = A + B(F_{M_{O_2}} - k)$$
$$= A - B \cdot k + B \cdot F_{M_{O_2}}$$

$$\text{Also } F_{I_3} = A + B(F_{I_2} - k)$$
$$= A(1 + B) - (B + B^2) \cdot k + B^2 \cdot F_{M_{O_2}}$$

$$\text{and } F_{I_4} = A(1 + B + B^2) - (B + B^2 + B^3) \cdot k + B^3 \cdot F_{M_{O_2}}$$

and, in general,

$$F_{I_n} = A(1 + B + B^2 + \ldots + B^{n-2}) - (B + B^2 + \ldots + B^{n-1}) \cdot k + B^{n-1} \cdot F_{M_{O_2}}$$

Now $B = y/V_T$, and since $y < V_T$ by definition, B is fractional. Therefore, in the limit, as the number of respiratory cycles becomes very large, and $n \to \infty$

$$F_{I_\infty} = \frac{A}{(1 - B)} - \frac{k \cdot B}{(1 - B)}$$
$$= F_{M_{O_2}} - \frac{k \cdot y}{x} \ldots\ldots (4)$$

Since all the terms on the right-hand side of this equation are assumed constant, F_{I_∞} is constant.

It is therefore established that where $z = 1$, the concentration of oxygen inspired will approach a certain limiting value as the number of respiratory cycles increases. There is no reason to suppose that the attainment of a steady state is a property confined to systems for which $z = 1$, although the formal proof of this is not obvious.

It will be assumed, then, that whatever the value of z, as $n \to \infty$ a steady state will eventually be reached, after which no further change in F_I occurs. When this steady state is attained

$$F_{I_{(n-z)}} = F_{I_n} = F_{I_\infty}$$

Substituting in equation (2),

$$F_{I_\infty} = \frac{x}{V_T} \cdot F_{M_{O_2}} + \frac{y}{V_T} \cdot (F_{I_\infty} - k)$$

$$\therefore \quad F_{I_\infty} = F_{M_{O_2}} - \frac{k \cdot y}{x}$$

This is identical with equation (4). Hence if the attainment of a steady state is accepted, F_{I_∞} is independent of the value of z.

Thus equation (4) represents a general solution for the equilibrium concentration of oxygen in the gases inspired from any semiclosed system.

No further progress is possible until x and y can be evaluated. These quantities must be functions of certain variables operating in the system, such as gas flowrates, but the functions themselves must be assumed to vary from one semiclosed system to another, depending upon the permanent physical characteristics of the system.

TO-AND-FRO SYSTEMS

Consider the to-and-fro system represented by System I in figure 1. A and B represent the positions of the fresh gas inlet and of the expiratory valve respectively. Let V_{AB} be the volume of the tubing between A and B, and assume that no longitudinal mixing of gases occurs in the system at any time during its operation, except in the reservoir bag.

Then on inspiration the volume of the reservoir bag decreases by an amount ΔV, where

$$\Delta V = V_T - \dot{V}_M \cdot t_1$$

On expiration this volume is replaced in time t', at which point the expiratory valve opens. The bag is now full and no further volume change takes place in the system until the next inspiration begins. During the time t' a volume $\dot{V}_M \cdot t'$ enters the bag (or the corrugated tubing leading to the bag) from the machine. Hence the volume of expired gas entering the tubing to the left of B

$$= \Delta V - \dot{V}_M \cdot t'$$
$$= V_T - \dot{V}_M(t_1 + t') \quad \text{.....(5)}$$

(Mapleson, 1954)

Thus, at the instant when the expiratory valve opens, the front of the expired gas will lie at some point C, which may be either to the right or left of A depending on the relative magnitude of V_{AB}.

During the remainder of the respiratory cycle, a volume $\dot{V}_M(t_2 - t')$ of fresh gas enters the system at A and flows towards B, driving out its own volume of expired gas from the expiratory valve. There are two possible consequences of this, according as V_{AB} is greater or less than $\dot{V}_M(t_2 - t')$.

Case 1. $V_{AB} > \dot{V}_M(t_2 - t')$

In this case AB will not be completely scavenged of expired gas during the period $(t_2 - t')$, and when the next inspiration begins a volume $V_T - \dot{V}_M(t_1 + t') - \dot{V}_M(t_2 - t')$ of expired gas will remain in AB. This expired gas will form the first part of the ensuing inspiration, and represents the quantity y which is rebreathed. The remainder of the inspiration contains only fresh gases from the machine.

$$\therefore \quad y = V_T - \dot{V}_M(t_1 + t') - \dot{V}_M(t_2 - t')$$
$$= V_T - \dot{V}_M \cdot t$$
$$\therefore \quad x = \dot{V}_M \cdot t$$

The same result is arrived at by postulating that since V_{AB} is greater than $\dot{V}_M(t_2 - t')$, no fresh gas will escape from the expiratory valve at any time. Hence the entire input of fresh gases remains available in the system for inspiration, and therefore $x = \dot{V}_M \cdot t$

Substituting these values of x and y in equation (4), we have

$$F_{I_\infty} = F_{M_{O_2}} - \frac{k(V_T - \dot{V}_M \cdot t)}{\dot{V}_M \cdot t}$$

But $V_T = \dot{V}_T \cdot t$, since $t = 1/f$.

$$\therefore \quad F_{I_\infty} = F_{M_{O_2}} - k\frac{(\dot{V}_T - \dot{V}_M)}{\dot{V}_M} \quad \text{..... .....(6)}$$

The system where $V_{AB} > \dot{V}_M(t_2 - t')$ is, of course, equivalent to Magill's system (Mapleson's (1954) System A). Since this system utilizes the entire fresh gas inflow for inspiration, it achieves the maximum possible efficiency for any semi-closed system in respect of inspired oxygen concentrations.

The term "Maximal efficiency system" (M.E.S.) will henceforward be used in this paper for any semiclosed system in which $x = \dot{V}_M \cdot t$.

Case 2. $V_{AB} < \dot{V}_M(t_2 - t')$.

In this case, AB will be completely scavenged of expired gas during the expiratory pause, and in addition, a volume $\{\dot{V}_M(t_2 - t') - V_{AB}\}$ of fresh gas will be blown off from the expiratory valve and lost to the system. Now this is the only loss of fresh gas which occurs at any stage of the respiratory cycle; hence at each cycle a volume

$$\dot{V}_M \cdot t - \{\dot{V}_M(t_2 - t') - V_{AB}\}$$

of fresh gas is retained to be inspired by the patient.

$$\therefore \quad x = \dot{V}_M \cdot t - \{\dot{V}_M(t_2 - t') - V_{AB}\}$$

Since $V_{AB} < \dot{V}_M(t_2 - t')$,

the quantity $\{\dot{V}_M(t_2 - t') - V_{AB}\}$ is positive. Therefore $x < \dot{V}_M \cdot t$, and the system will provide an inspired oxygen concentration smaller than is the case when $V_{AB} > \dot{V}_M(t_2 - t')$; i.e. the system is not a maximal efficiency system.

The foregoing analysis of Case 2 may be criticized on the grounds that since AB is completely scavenged of expired gas during the expiratory pause, there can be no rebreathing whatsoever, and the system should therefore be a maximal efficiency system. The fallacy of this argument may be demonstrated as follows:

The volume of expired gas, V_E, entering AB during t′ is $V_T - \dot{V}_M(t_1 + t')$.

But $t_1 + t' = t - (t_2 - t')$

Therefore $V_E = V_T - \dot{V}_M \cdot t + \dot{V}_M(t_2 - t')$

Now $\dot{V}_M(t_2 - t') > V_{AB}$, and $V_T > \dot{V}_M \cdot t$, by assumption. Therefore $V_E > V_{AB}$, and at the time the new inspiration begins, a volume $(V_E - V_{AB})$ of expired gas remains in the tubing to the left of A.

But

$$\begin{aligned} V_E - V_{AB} &= V_T - \dot{V}_M \cdot t + \dot{V}_M(t_2 - t') - V_{AB} \\ &= V_T - x \\ &= y. \end{aligned}$$

Hence the entire volume of expired gas which remains in the system is rebreathed at the next inspiration, and since there is an escape of fresh gases from the valve, the condition for maximal efficiency is not met.

Case 2 represents Mapleson's (1954) Systems B and C. The disadvantage of these systems as compared to Magill's is not merely that they are uneconomical with respect to oxygen, but that they are unpredictable as regards the oxygen concentration delivered to the patient, owing to the fact that the values of $\dot{V}_M(t_2 - t')$ and V_{AB} are usually indeterminate.

DYNAMICS OF CIRCLE SYSTEMS

The major obstacle to any theoretical treatment of circle systems is the fact that the gas flows in the system are discontinuous. If the patient's lungs behaved like a rotary pump producing a continuous circulation of gas around the system the difficulties would largely vanish.

It may be supposed that one of the consequences of the discontinuous flow is that the mean concentration of oxygen inspired varies from breath to breath. Nevertheless, if the eventual attainment of a steady state is accepted, then the mean inspired oxygen concentration measured over, say, ten successive inspirations, must be reproduced over the following ten inspirations. By an extension of the same argument, it is reasonable to suppose that the mean inspired oxygen concentration over a large number of inspirations will be equal to the mean concentration inspired by a patient whose lungs behaved as a continuously acting pump.

In the analyses which follow the patient is therefore treated as a rotary pump which continuously abstracts gas from and returns gas to the circuit at a rate of $\dot{V}_T$ litres/minute.

Two circle systems will be considered, the first having the expiratory valve at the face mask fitting, and the second having the expiratory valve at a point remote from the patient. In each case the inlet for fresh gases is assumed to be remote from the patient, and in order to simplify the analysis, the inspired oxygen concentration is calculated directly, without a preliminary evaluation of x and y.

A circle system with the expiratory valve at the face mask fitting.

In System II, figure 1, the gases flow in the direction ABCDA. Since the gas flow is unidirectional, the volume of gas entering CD in the course of a single respiratory cycle is:

During t_1 .....None.

During t′ .....$V_T - \dot{V}_M \cdot t_1$. (This is the volume required to replace the gas removed from the bag during inspiration.)

During $t_2 - t'$ ...None.

Therefore during the entire respiratory cycle, t minutes, the volume of gas entering CD is $V_T - \dot{V}_M \cdot t_1$

$\therefore$ Volume of gas entering CD per minute

$$= \frac{V_T}{t} - \dot{V}_M \cdot \frac{t_1}{t}$$

$$= \dot{V}_T - \dot{V}_M \cdot \frac{t_1}{t}$$

Now this volume is made up partly of gas passing directly from BC during t′, and partly of gas expired by the patient during t′. The volume which comes into CD from BC in the course of one minute is $\dot{V}_M \cdot \frac{t'}{t}$ and the volume which comes in after being expired by the patient is therefore

$$\dot{V}_T - \dot{V}_M \cdot \frac{t_1}{t} - \dot{V}_M \cdot \frac{t'}{t} = \dot{V}_T - \dot{V}_M \frac{(t_1 + t')}{t}$$

If the mean oxygen concentration in BC is $\bar{F}I_{O_2}$, then the volumes of oxygen contained in these two portions of gas are:

FIG. 1

The three semiclosed systems.

FIG. 2

Inspired oxygen concentrations for various fresh gas flowrates, using a circle system with the expiratory valve at the face mask fitting (System II, equation 7). The uppermost and lowermost curves represent the extremes for this type of system, the former being the curve obtained when $(t_1 + t')/t$ has the idealized value of unity, for which the system becomes a M.E.S.
In all cases, $\dot{V}_T = 8$ litres/min, $F_{M_{O_2}} = 0.5$, $k = 0.05$

In the portion from BC

$$\bar{F}I_{\infty} \cdot \dot{V}M \cdot \frac{t'}{t}$$

In the portion from the patient

$$\left(\dot{V}T - \dot{V}M \cdot \frac{(t_1 + t')}{t}\right) \cdot (\bar{F}I_{\infty} - k)$$

The total mean flowrate of oxygen per minute through CDA is therefore the sum of these oxygen volumes. At A, more oxygen enters from the machine at the rate of $\dot{V}M \cdot FM_{O_2}$ litres per minute.

Hence the total mean flowrate of oxygen through ABC is:

$$\dot{V}M \cdot FM_{O_2} + \bar{F}I_{\infty} \cdot \dot{V}M \cdot \frac{t'}{t} + \left(\dot{V}T - \dot{V}M\frac{(t_1 + t')}{t}\right) \cdot (\bar{F}I_{\infty} - k)$$

But the total flowrate of all gases through ABC is

$$\dot{V}T - \dot{V}M \cdot \frac{t_1}{t} + \dot{V}M$$

$$\therefore \bar{F}I_{\infty}\left(\dot{V}T - \dot{V}M \cdot \frac{t_1}{t} + \dot{V}M\right) = \dot{V}M \cdot FM_{O_2} + \bar{F}I_{\infty} \cdot \dot{V}M \cdot \frac{t'}{t} + \left(\dot{V}T - \dot{V}M\frac{(t_1 + t')}{t}\right) \cdot (\bar{F}I_{\infty} - k)$$

$$\therefore \bar{F}I_{\infty} = FM_{O_2} - k\left(\frac{\dot{V}T}{\dot{V}M} - \frac{(t_1 + t')}{t}\right) \quad \text{.....(7)}$$

A circle system with the expiratory valve remote from the face mask.

In System III, figure 1, the gases flow in the direction ABCDA. When the steady state is reached, let $\bar{F}I_{\infty}$ be the mean oxygen concentration in AB.

The volume of gas entering CD in the course of a single respiratory cycle is:

During t_1 .....None.

During t_2 .....VT from patient, and $\dot{V}M \cdot t_2$ direct from B.

Therefore, during the entire respiratory cycle, t minutes, the volume of gas entering CD is $VT + \dot{V}M \cdot t_2$

$\therefore$ Volume of gas entering CD per minute

$$= \frac{VT}{t} + \dot{V}M \cdot \frac{t_2}{t}$$

$$= \dot{V}T + \dot{V}M \cdot \frac{t_2}{t}$$

Put $\dot{V}T + \dot{V}M \cdot \frac{t_2}{t} = b$

Then b represents the mean minute flowrate of gases in CD, and therefore also in AB, since the respiratory quotient is assumed to be unity.

Since a steady state is postulated, the volume of gas leaving the system via the expiratory valve in one minute must be equal to the volume entering from the machine in one minute, i.e. to $\dot{V}M$.

$\therefore$ Mean minute flowrate in DA $= b - \dot{V}M$

Now the volume of oxygen entering CD per minute

$$= \dot{V}T(\bar{F}I_{\infty} - k) + \dot{V}M \cdot \frac{t_2}{t} \cdot \bar{F}I_{\infty}$$

$$= b \cdot \bar{F}I_{\infty} - k \cdot \dot{V}T$$

Therefore the mean concentration of oxygen in CD

$$= \frac{b \cdot \bar{F}I_{\infty} - k \cdot \dot{V}T}{b}$$

$$= \bar{F}I_{\infty} - \frac{k \cdot \dot{V}T}{b}$$

The mean concentrations of oxygen in CD and DA must be equal.

Therefore the mean flowrate of oxygen through DA

$$= (b - \dot{V}M) \cdot \left(\bar{F}I_{\infty} - \frac{k \cdot \dot{V}T}{b}\right)$$

$$= (b - \dot{V}M) \cdot \bar{F}I_{\infty} - \frac{k \cdot \dot{V}T}{b}(b - \dot{V}M)$$

Therefore the mean flowrate of oxygen through AB

$$= \dot{V}M \cdot FM_{O_2} + (b - \dot{V}M) \cdot \bar{F}I_{\infty} - \frac{k \cdot \dot{V}T}{b}(b - \dot{V}M)$$

But the total mean flowrate of oxygen through AB $= b \cdot \bar{F}I_{\infty}$

$$\therefore b \cdot \bar{F}I_{\infty} = \dot{V}M \cdot FM_{O_2} + (b - \dot{V}M) \cdot \bar{F}I_{\infty} - \frac{k\,\dot{V}T}{b} \cdot (b - \dot{V}M)$$

$$\therefore \quad \bar{F}I_{\infty} = FM_{O_2} - k \cdot \left(\frac{\dot{V}T}{\dot{V}M} - \frac{\dot{V}T}{\dot{V}T + a \cdot \dot{V}M}\right) \quad \text{.....(8)}$$

where $a = t_2/t$.

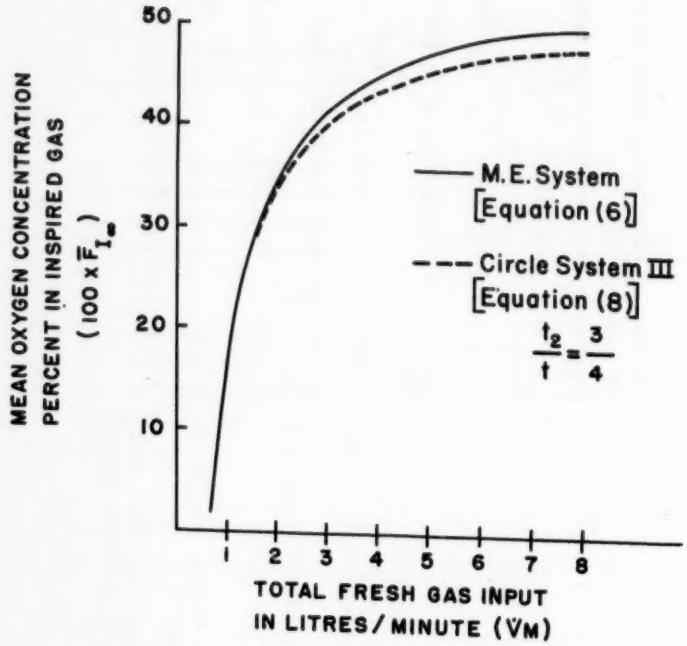

FIG. 3

Inspired oxygen concentrations for various fresh gas flowrates, using a circle system with the expiratory valve remote from the face mask (System III, equation 8). The two curves shown represent the extremes for this type of system, the upper one being the curve obtained when t_2/t has the idealized value of zero, for which the system becomes a M.E.S.

In both cases, $\dot{V}_T = 8$ litres/min, $F_{M_{O_2}} = 0.5$, $k = 0.05$

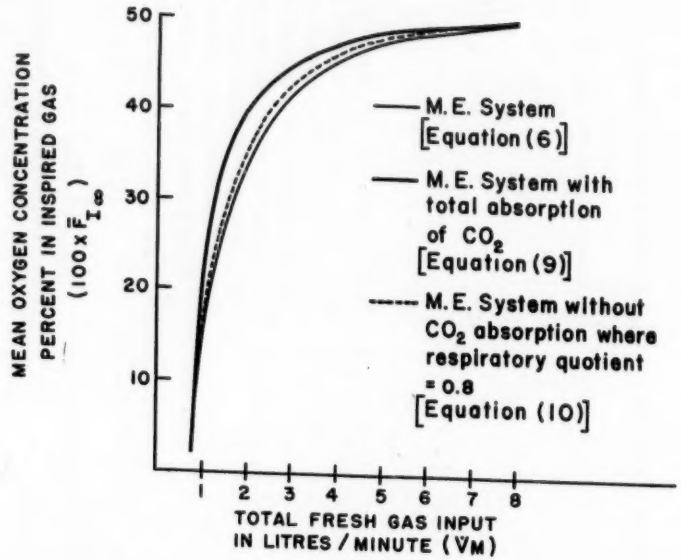

FIG. 4

Inspired oxygen concentrations for various fresh gas flowrates. All curves represent a M.E.S. The lowermost and uppermost curves respectively represent the system when carbon dioxide is not absorbed and when it is completely absorbed. In each of these two cases R = 1. The intermediate curve represents a M.E.S. where no carbon dioxide is absorbed and where R = 0.8

In all cases, $\dot{V}_T = 8$ litres/min, $F_{M_{O_2}} = 0.5$, $k = 0.05$

THE CONSEQUENCES OF INCLUDING A CARBON DIOXIDE ABSORBER IN THE SYSTEM

If the input of fresh gases into a semiclosed system is small in relation to the patient's minute volume, a carbon dioxide absorber must be included in the system to avoid hypercarbia. The foregoing analyses have ignored the effects of carbon dioxide absorption in order to simplify the calculations.

It will now be shown that any alterations in inspired oxygen concentrations caused by the presence of an absorber must be in the patient's favour; i.e. the calculated concentration will be smaller than the actual concentration.

The net effect of the reactions taking place between carbon dioxide and the constituents of the soda lime may be expressed as follows:

$$2CO_2 + 2NaOH + Ca(OH)_2 \rightarrow Na_2CO_3 + CaCO_3 + 2H_2O$$

Thus for every molecule of carbon dioxide absorbed, one molecule of water is liberated. If the water remains in the system as water vapour it replaces precisely the volume of carbon dioxide which was absorbed. Hence, in the absence of condensation, there is no volume change consequent upon carbon dioxide absorption, and no correction is necessary in equation (4).

In practice this condition is probably not often achieved. It is common to find several millilitres of water condensed in the tubing after a long anaesthetic; some of this water comes from the expired gases; some, no doubt, from the carbon dioxide absorber. Moreover, some water vapour is taken up by the sodium hydroxide in the soda lime. Thus it may be anticipated that in most cases the use of an absorber causes some volume change in the system in the direction of an effective decrease in the volume of expired gas. Since there is no loss of oxygen in the absorber, the effective oxygen concentration in the expired gas becomes higher than the theoretical concentration.

Now in any semiclosed system in which the various gas flows are constant, the values of x and y are fixed by the physical characteristics of the system. Hence, no matter how much volume change is caused by absorption of carbon dioxide, the value of y cannot alter. Compensation is made instead by an alteration in the volume of expired gas blown off through the expiratory valve during the time $(t_2 - t')$.

Thus in equation (1) the value of $F_{E(n-z)}$ is made slightly larger when a carbon dioxide absorber is placed in the circuit. It follows therefore, that the value of $F_{I\infty}$ as calculated from equation (4) will be too low; it will only be correct if all the water formed by the reactions in the absorber remains in the system in the form of vapour.

Consider the state of affairs when Magill's system is used with a Waters canister adjacent to the face mask, and all the water formed is condensed. Let the respiratory quotient be R. Then during a single respiratory cycle:

Volume of gas inspired $= V_T$

Volume of oxygen extracted from this inspired gas $= k \cdot V_T$

Volume of carbon dioxide expired $= k \cdot R \cdot V_T$

$\therefore$ Oxygen concentration in expired gas *before* absorption of carbon dioxide

$$= \frac{V_T \cdot F_{I\infty} - k \cdot V_T}{V_T - k \cdot V_T + k \cdot R \cdot V_T}$$

$$= \frac{F_{I\infty} - k}{1 - k(1 - R)}$$

After absorption of carbon dioxide, the oxygen concentration becomes

$$\frac{V_T \cdot F_{I\infty} - k \cdot V_T}{V_T - k \cdot V_T}$$

$\therefore$ After carbon dioxide absorption

$$F_{E\infty} = \frac{F_{I\infty} - k}{1 - k}$$

From equation (1)

$$F_{I\infty} = \frac{x}{V_T} \cdot F_{M_{O_2}} + \frac{y}{V_T} \cdot F_{E\infty}$$

$$\therefore \quad F_{I\infty} = \frac{x}{V_T} \cdot F_{M_{O_2}} + \frac{y \cdot (F_{I\infty} - k)}{V_T \cdot (1 - k)}$$

Giving x and y the values $\dot{V}_M \cdot t$ and $(\dot{V}_T \cdot t - \dot{V}_M \cdot t)$ respectively, for a maximal efficiency system,

$$F_{I\infty} = \frac{\dot{V}_M(1 - k) \cdot F_{M_{O_2}} - k \cdot (\dot{V}_T - \dot{V}_M)}{\dot{V}_M - k \cdot \dot{V}_T} \qquad \text{.....(9)}$$

If carbon dioxide is not absorbed (or, if it is absorbed and all the water formed remains as vapour), then it can be shown in a similar way that for a maximal efficiency system

$$\bar{F}I_{O_2} = \frac{\dot{V}M\{1 - k(1 - R)\} \cdot FM_{O_2} - k \cdot (\dot{V}T - \dot{V}M)}{\dot{V}M - k \cdot \dot{V}T \cdot (1 - R)} \quad \ldots\ldots\ldots\ldots(10)$$

It is evident from equation (9) that in systems where all carbon dioxide is absorbed and all water condensed, the final concentration of oxygen inspired is independent of the value of the respiratory quotient. In practice such a condition will rarely, if ever, be obtained, and the actual value of $\bar{F}I_{O_2}$ will lie somewhere between the two extreme values given by equations (9) and (10).

The quantitative effects of using these equations rather than equation (6) for the determination of $\bar{F}I_{O_2}$ will be demonstrated graphically at a later stage.

THE VALUE OF k AND THE LIMITATIONS OF ITS CONSTANCY

In maximal efficiency systems equation (6) provides a useful guide to the flowrates of oxygen and nitrous oxide required to maintain a satisfactory concentration of oxygen in the inspired gas. The only quantity on the right-hand side of this equation which cannot be measured directly by the anaesthetist is k. However, the value of this constant in normal adults is known to be 0.05 ± 0.005 (Richards, 1950). For the present purposes its value may be assumed to be 0.05.

Hence equation (6) becomes

$$\bar{F}I_{O_2} = FM_{O_2} - 0.05\,\frac{(\dot{V}T - \dot{V}M)}{\dot{V}M} \quad \ldots\ldots(11)$$

where $\dot{V}M$ is not greater than $\dot{V}T$, and for maximal efficiency systems only.

In deriving this and all the other equations for $\bar{F}I_{O_2}$, it has been assumed that the value of k is constant and independent of the value of $\bar{F}I_{O_2}$; i.e. that the volume of oxygen abstracted by the pulmonary blood at each respiratory cycle is constant and independent of the inspired oxygen concentration.

In fact, of course, the volume abstracted will depend upon the alveolar partial pressure of oxygen.

However, from the shape of the oxyhaemoglobin dissociation curve for human blood, provided that the mean alveolar oxygen partial pressure exceeds 90 mm Hg, the blood will be approximately saturated, and therefore for alveolar oxygen partial pressures above 90 mm Hg there will be no significant error in equation (11).

If the alveolar partial pressure of oxygen falls below 90 mm Hg, the blood will leave the lungs with an oxygen saturation significantly less than 100 per cent, i.e. a smaller volume of oxygen will be absorbed at each respiration.

Now, assuming still that the respiratory quotient is unity,

$P_{A_{O_2}} = P_{I_{O_2}} - P_{A_{CO_2}}$ (Comroe et al., 1955).

If a carbon dioxide absorber is in use, and the $P_{A_{CO_2}}$ is maintained at 40 mm Hg,

$$P_{I_{O_2}} = P_{A_{O_2}} + 40$$

Therefore the minimal value of $P_{I_{O_2}}$ which permits k to be regarded as constant is given by

$$P_{I_{O_2}} = 90 + 40 = 130 \text{ mm Hg}$$

Therefore the limiting value of $\bar{F}I_{O_2}$ which permits k to be regarded as constant is given by

$$\bar{F}I_{O_2} = 130/760 = 0.17 \text{ approximately}$$

Where $\bar{F}I_{O_2}$ is less than 0.17, the calculated value of $\bar{F}I_{O_2}$ may be expected to be less than the true value. This source of error, however, is of little practical importance, since the anaesthetist seeks at all times to maintain the inspired oxygen concentration at a level higher than 17 per cent.

DISCUSSION

(a) *Maximal efficiency systems.* It has already been explained that equation (6) represents the optimum in semiclosed systems as far as inspired oxygen concentrations are concerned. It will therefore be used in this discussion as a standard for comparison and as a model for an ideal semiclosed system.

If graphs of equation (6) are plotted, using $\bar{F}I_{O_2}$ as ordinate and $\dot{V}M$ as abscissa, and giving various values to FM_{O_2} and $\dot{V}T$, a family of curves is obtained. For the sake of illustration one member of this family has been selected, and the solid line in figures 2, 3 and 4 represents equation (6) when $\dot{V}T$ and FM_{O_2} have the values of 8 litres per minute and 0.5 respectively, and $k = 0.05$.

It will be seen from this curve that in order to maintain an inspired oxygen concentration of 21 per cent, the total fresh gas flowrate from the machine must be about 1.177 litres per minute, i.e. 0.588 litres per minute of oxygen and 0.588 litres per minute of nitrous oxide, approximately.

By putting $\dot{V}_M = \dot{V}_T$ in equation (6), $\bar{F}_{I_\infty}$ becomes equal to $F_{M_{O_2}}$. When $\dot{V}_M < \dot{V}_T$, $\bar{F}_{I_\infty} < F_{M_{O_2}}$. This important result may be restated in words:

In a semiclosed system of maximal efficiency type, the concentration of oxygen in the gases inspired by the patient will be less than the concentration of oxygen in the fresh gases entering the system except when the total minute flow of fresh gas equals or exceeds the patient's minute volume.

This rule requires some further explanation, in so far as the maximum value, mathematically, of the function

$$F_{M_{O_2}} - k \cdot \frac{(\dot{V}_T - \dot{V}_M)}{\dot{V}_M}$$

is not $F_{M_{O_2}}$, but $(F_{M_{O_2}} + k)$. This mathematical maximum occurs when $\dot{V}_M$ becomes infinitely large, but it would appear that if $\dot{V}_M$ is given any value greater than $\dot{V}_T$, $\bar{F}_{I_\infty}$ should be greater than $F_{M_{O_2}}$, which is absurd. This paradox is explained when it is remembered that, in order to derive equation (6), it was postulated that $\dot{V}_M$ should be not greater than $\dot{V}_T$. Hence, for values of $\dot{V}_M$ exceeding $\dot{V}_T$, the curve has no meaning, and in practice $\bar{F}_{I_\infty}$ can never exceed $F_{M_{O_2}}$.

(b) *Circle systems.* Some criticism may be directed at the continuous flow treatment used to derive equations (7) and (8) for circle systems. In fact, attempts to deal with discontinuous flows were found to be even less satisfactory, and led to the conclusion that circle systems approximate to maximal efficiency systems only for values of $\dot{V}_M$ which are close to $\dot{V}_T$. It was therefore surprising to note that Swartz, Adriani and Mih (1953) found no significant differences between the oxygen concentrations delivered by systems equivalent to I (Magill's), II, and III, of figure 1.

In the light of this experimental finding, a new approach to circle systems was sought, and the continuous flow treatment was found to give much better agreement with the measured oxygen concentrations.

Equations (7) and (8) contain the terms $(t_1 + t')/t$ and t_2/t respectively. These ratios are indeterminate in ordinary circumstances but certain limits can be assigned to their values. Thus the value of $(t_1 + t')/t$ will almost certainly lie between 0.25 and 1.0, and t_2/t will almost certainly lie between 0 and 0.75.

Hence, if two graphs of equation (7) are drawn, for values of $(t_1 + t')/t$ equal to 0.25 and 1.0, it can be stated that the area enclosed by these two curves must almost certainly contain the particular curve characteristic of any given example of System II, assuming that the other constants have the same values as were used for the boundary curves.

Likewise, if two graphs of equation (8) are plotted, giving t_2/t the values 0 and 0.75, then the area enclosed by the two must contain the curve characteristic of any example of System III, the constants being the same.

When $(t_1 + t')/t = 1$, equation (7) becomes identical with equation (6). When $t_2/t = 0$, equation (8) becomes identical with equation (6). Hence, for these idealized values of the time ratios, Systems II and III become maximal efficiency systems.

Figures 2 and 3 show the curves obtained by giving $(t_1 + t')/t$ and t_2/t the values 0.25 and 0.75 respectively. (In each case, $\dot{V}_T$ is taken as 8 litres per minute, $F_{M_{O_2}}$ as 0.5, and k as 0.05, as before.)

It will be observed that both these curves lie below the curve for a maximal efficiency system, and the areas enclosed by the two curves on each figure represent the limits for any example of either system.

Let $\Delta\bar{F}_{II}$ represent the difference between the oxygen concentration delivered by a maximal efficiency system and that delivered under identical conditions from System II. Then, by subtracting equation (7) from equation (6),

$$\bar{F}_{II} = k\left\{1 - \frac{(t_1 + t')}{t}\right\}$$

This expression will have its maximum value when $(t_1 + t')/t$ is a minimum, i.e. when $(t_1 + t')/t = 0.25$.

$$\therefore \quad \Delta\bar{F}_{II(max)} = 0.05(1 - 0.25) = 3.75\%.$$

$$\text{Similarly, } \Delta\bar{F}_{III} = \frac{k \cdot \dot{V}_M}{\dot{V}_T \cdot \frac{t}{t_2} + \dot{V}_M}$$

This expression will be a maximum when $\dot{V}_M = \dot{V}_T$ and t/t_2 is minimal; t/t_2 is minimal when t_2/t is 0.75.

$$\therefore \quad \Delta\bar{F}_{III}\,(\text{max}) = \frac{0.05}{\frac{1}{0.75} + 1}$$

$$= 2.14\% \text{ approximately.}$$

In practice, the values of $\Delta\bar{F}_{II}$ and $\Delta\bar{F}_{III}$ are probably usually considerably smaller than these maxima, and may well be too small to have appeared significant to the experimental workers in this field. This is at least a possible explanation of the inability of Swartz, Adriani and Mih (1953) to demonstrate any differences between the three systems considered.

As in the case of a maximal efficiency system, the maximal value of $\bar{F}_{I\infty}$ obtainable in practice from a circle system must be $F_{M_{O_2}}$, but in order to achieve this maximum oxygen concentration, $\dot{V}_M$ must be made bigger than $\dot{V}_T$. In the case of System II, from equation (7), for maximum inspired oxygen concentration

$$\dot{V}_M \geqslant \frac{t \cdot \dot{V}_T}{(t_1 + t')}$$

and in the case of System III, from equation (8), for the same condition,

$$\dot{V}_M \geqslant \frac{t \cdot \dot{V}_T}{(t - t_2)}$$

$$\geqslant \frac{t}{t_1} \cdot \dot{V}_T$$

(c) *Carbon dioxide absorption.* Although the important matter of carbon dioxide absorption has been ignored in the derivation of the basic equations for the three systems considered, it is taken for granted that where low flowrates of fresh gases are used adequate provision will always be made for removal of expired carbon dioxide.

When an absorber is in use its efficiency is variable, and may not be predictable with great accuracy. It can be said, however, that the effects of the absorber must lie somewhere between the following extremes:

(i) Total carbon dioxide absorption with complete condensation of all water formed, which implies a consequent volume change equal to the volume of carbon dioxide absorbed.

(ii) Complete absence of carbon dioxide absorption; or, alternatively, partial or complete absorption with all water formed remaining in the system as vapour. Either of these alternatives implies that no volume change takes place in the system.

The first extreme is represented for a maximal efficiency system by equation (9), and the second by equation (6). Hence, if the graphs of these two equations are plotted together, the area enclosed between them must include all possible curves for every degree of efficiency of carbon dioxide absorption and water condensation. This is shown in figure 4. It will be observed that the curve for total absorption lies above the curve for no absorption, except for values of $\dot{V}_M$ which are very small, and where $\dot{V}_M$ is equal to or greater than $\dot{V}_T$.

This emphasizes the point previously made, that the use of carbon dioxide absorption causes an error in the theoretical inspired oxygen concentration which is in the patient's favour. It also confirms the following rule, which has already been proved for Magill's system by Mapleson (1954), but which may now be extended to any maximal efficiency system:

In any semiclosed system of maximal efficiency type, where no carbon dioxide absorber is in use, the expired carbon dioxide will not be completely scavenged unless the total minute flow of fresh gas from the machine equals or exceeds the patient's minute volume.

This rule is proved mathematically by subtracting equation (6) from equation (9), equating the difference to zero, and solving for $\dot{V}_M$.

(d) *The respiratory quotient.* The curve obtained by putting $R = 0.8$ in equation (10) is shown in figure 4. This corrected curve lies slightly above that of equation (6), but the two are so close together that it would seem reasonable to regard all patients as having a respiratory quotient of unity for the purposes here considered. In any case, the small error which this assumption involves is in the patient's favour.

Finally, it must be emphasized that this entire

paper is theoretical, and since the author has not attempted to confirm his predictions experimentally, no claim is made that they are necessarily correct. However, semiclosed systems are widely used in anaesthesia, and it seems fitting that some attempt should be made to develop theories upon which their practical application can be based, and which can be put to the test of experiment.

SUMMARY

(1) It is shown theoretically that when a patient breathes for a long period from any semiclosed system, the inspired oxygen concentration falls progressively to a definite limit, after which no further change occurs and a steady state is reached.

(2) A theoretical method of predicting the oxygen concentration in the gases delivered by three semiclosed systems is presented, and it is shown that no semiclosed system can be more efficient than Magill's in respect of oxygen concentration delivered.

(3) It is shown that in an ideal (maximal efficiency) semiclosed system, such as Magill's, a total minute flow of fresh gases equal to the patient's respiratory minute volume will eliminate rebreathing of expired carbon dioxide without the need for a soda lime absorber, and will also ensure delivery of a gas mixture to the patient containing oxygen in a concentration equal to that in the fresh gases entering from the machine.

(4) The effects of carbon dioxide absorption and of variations in the patient's respiratory quotient on the predicted oxygen concentrations are discussed.

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REFERENCES

Comroe, J. H., Forster, R. E., Dubois, A. B., Briscoe, W. A., Carlsen, E. (1955). *The Lung*, 1st ed., p. 184. Chicago: The Year Book Publishers.

Crowley, J. H., Faulconer, A., and Lundy, J. S. (1948). Certain factors influencing the percentage of oxygen in mixtures of nitrous oxide and oxygen. *Curr. Res. Anesth.*, **27**, 255.

Foldes, F. F., Ceravolo, A. J., and Carpenter, S. L. (1952). The administration of nitrous oxide-oxygen anesthesia in closed systems. *Ann. Surg.*, **136**, 978.

Luciani, L. (1911). *Human Physiology*. 1st English ed., p. 384. London: Macmillan.

Mapleson, W. W. (1954). The elimination of rebreathing in various semiclosed anaesthetic systems. *Brit. J. Anaesth.*, **26**, 323.

Molyneux, L., and Pask, E. A. (1951). The flow of gases in a semiclosed anaesthetic system. *Brit. J. Anaesth.*, **23**, 81.

Pappenheimer, J. R. (1950). Standardization of definitions and symbols in respiratory physiology. *Fed. Proc.*, **9**, 602.

Richards, D. W. (1950). *Medical Physics*. Edited by Glasser, O., 1st ed., Vol. II, p. 842. Chicago: The Year Book Publishers.

Ruben, H. M. (1953). Concerning the concentration of inhaled gases in semiclosed anesthesia systems. *Anesthesiology*, 14, 459.

Swartz, C. H., Adriani, J., and Mih, A. (1953). Semiclosed inhalers: Studies of oxygen and carbon dioxide tensions during various conditions of use. *Anesthesiology*, **14**. 437.

Brit. J. Anaesth. (1958), **30**, 282

REGULATION OF CONTROLLED RESPIRATION: RECENT CONCEPTS IMPORTANT TO THE ANAESTHETIST

BY

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DURING the past few years our knowledge of respiratory mechanics has taken great strides forward, and has now reached a point where ventilatory requirements during anaesthesia can be predicted for almost every patient. These forecast values may be applied to advantage when automatically controlled pulmonary ventilation is desirable.

The considerations which follow provide the basis for computing ventilatory parameters for the healthy patient and, with suitable adjustments, can be applied also to those with emphysema, low blood volume and poor myocardial function. The recommendations which follow have been tried out in over 500 major operations, including 125 intrathoracic procedures, and have been found to be valid and reliable. The main factors fall into two classes: those involving the anaesthetic circuit, and those related to the patient's airway, lungs and heart.

FACTORS INVOLVING ANAESTHETIC CIRCUIT

Six anaesthetic circuits are commonly used today in conjunction with controlled ventilation: the closed circle, closed to-and-fro, semiclosed circle, semiclosed to-and-fro, semiclosed Magill type and its modifications, and nonrebreathing systems. There are deficiencies and sources of error in all of these, which can be checked and avoided as follows. (*a*) Reduce resistance by using wide bore curved connectors and by inserting the largest endotracheal tube which can be admitted with ease. (*b*) Make sure that the nonreturn valves function without appreciable resistance, and close securely to prevent backflow (Hunt, 1955; Orkin et al., 1954, 1957). (*c*) When economy of gases or vapour is essential, the closed systems with cyclopropane or semiclosed systems with halothane may be used. (*d*) In the machine, use high grade carbon dioxide absorbent: one that breaks down into dust with gentle shaking is of poor quality and should not be used. Pack the absorbent firmly into the canister and set the latter upright to avoid channelling. Always check and record the time for which it has been in use. (*e*) The semiclosed system Magill type should be used mainly with spontaneous respiration, when light anaesthesia is sufficient with nitrous oxide and trichloroethylene. If assisted or controlled respiration is needed, this system should not be employed, because adequate ventilation is difficult to provide unless the patient is in the supine position or only in moderate deviation from it (Dobkin, 1958). In any case, the use of this system should be accompanied by a gas flow which is at least equal to the estimated minute volume of the patient breathing through an endotracheal tube (Mapleson, 1954; Woolmer and Lind, 1954). (*f*) The nonrebreathing system, when employed with controlled ventilation, must be provided with a valve whose expiratory vent is securely closed during the inspiratory phase of the respiratory cycle, and with a gas flow which exceeds the patient's minute volume of breathing.

In order to fulfil the above recommendations, it is essential also to provide the external anaesthetic circuit with gas ducts which are nondistensible. Otherwise elastic resistance to air movement and viscous resistance to air flow in the external airway increases the difficulty of calculating ventilatory requirements.

If all these suggestions are followed, respiratory acidosis will rarely occur due to factors outside the patient (Dobkin et al., 1956 a, b; Dobkin, 1958).

FACTORS RELATED TO PATIENT

Careful selection of the ventilatory parameters is necessary to provide normal respiration and to

avoid cardiovascular embarrassment. Allowance must be made also for certain alterations in the compliance of the lungs and resistance of the airways, which accompany existing disease and which are aggravated by general anaesthesia. The following factors are important:

(a) *Tidal volume.* This must be sufficient to remove the alveolar carbon dioxide and flush out the anatomical deadspace during each respiratory cycle. It can be assumed that the deadspace fraction of tidal volume is 1 ml/lb. (0.45 kg) body weight (Radford et al., 1954), if the patient's weight is within the normal weight limits for height, build and age noted in table I. Allow also for deadspace in the anaesthetic circuit (mechanical deadspace) and for internal (physiological) deadspace in the patient with emphysema. The physiological deadspace varies widely among patients with moderate to marked emphysema. Approximately 50 to 250 ml should be added to the tidal volume, according to the severity of the emphysema as judged by the physical signs, the amount of dyspnoea, and the expiration time. No adjustment for mechanical deadspace need be made when the closed circle, semiclosed circle or non-rebreathing systems are used, if the patient is intubated. When the semiclosed Magill system (Mapleson A) is used add 50–150 ml (according to the patient's body weight) to the tidal volume. A gas flow equal to the minute volume is sufficient to eliminate mixing in the delivery tube if the supine horizontal position is adopted, the expiratory valve opens at, or less than, 1 mm Hg and passes a large flow of gas at a low pressure gradient, and if the valve closes immediately at the start of inspiration when the flow rate rises instantaneously to 30–55 l./min. Otherwise, the gas flow from the anaesthetic machine must be at least twice the minute volume.

When these corrections are added to the volumes noted in table II, an effective minute volume (alveolar ventilation) in the 4 to 6 litre range is assured if the rate of breathing and pressure amplitude are suitably determined.

TABLE I

*Adult—Height and Weight without clothing.**

Height in.	Height cm	Age 15	20	25	30
		FEMALES			
56	142	90—113	95—117	97—122	100—125
58	147	92—115	98—123	101—126	104—129
60	152	96—120	103—128	104—131	107—134
62	157	102—127	108—135	111—138	113—141
64	162	108—135	113—142	116—145	119—149
66	167	115—144	121—151	123—154	126—158
68	172	122—153	127—159	131—163	133—167
70	178	131—163	134—168	137—171	140—174
		MALES			
60	152	94—117	103—128	107—134	111—138
62	157	99—124	108—135	112—139	115—114
64	162	105—131	114—143	119—148	122—152
66	167	113—140	122—152	126—157	129—161
68	172	120—149	129—161	133—166	136—170
70	177	128—159	136—170	141—176	145—181
72	183	137—171	145—181	151—189	156—194
74	188	146—182	154—192	161—201	167—208

* Weight in pounds, from the Life Extension Institute of New York City.
Range includes light to heavy build.
The ideal weight at 30 should be maintained throughout life.
Formula for ideal weight in kg=[height in cm−100] (Broca).

TABLE II

Tidal volume and rate of respiration for use in patients under general anaesthesia and pulmonary ventilation controlled through an endotracheal tube and nondistensible gas delivery tube. Inspiratory phase of respiratory cycle limited to 1 second in duration, and inspiratory peak pressure adjusted to 15 mm Hg.

Patient's "normal" weight	lb.	75	100	125	150	175	200
	kg.	34	45.5	57	68	79.5	91
Respiratory rate		Tidal volume (ml)					
16		—	—	500	550	600	650
18		—	450	475	500	550	600
20		350	375	400	450	500	550

(b) *Rate.* The selection of the rate of respiration is influenced by the minute volume required, the instantaneous rate at which the gas can be delivered, the need to reduce the work of breathing to a minimum, and the flushing effect required to clear the alveolar carbon dioxide of patients with emphysema (Christie, 1934; Otis et al., 1950; Dayman, 1951; Mead and Whittenberger, 1953; Fry et al., 1954; McIlroy and Christie, 1954; McIlroy et al., 1954; Mead et al., 1955; Butler and Arnott, 1955; Gordon et al., 1956).

In the average-sized adult a respiratory rate of 16 to 20 per minute has been found to be suitable in most clinical situations, as long as the airflow is at least 30 l./min, and can be increased to 50 l./min for the very large patient. When I.P.P. or P.N.P. is employed by hand, mechanically or automatically, the duration of inspiration should not exceed 1 second (Cournand et al., 1948; see fig. 1).

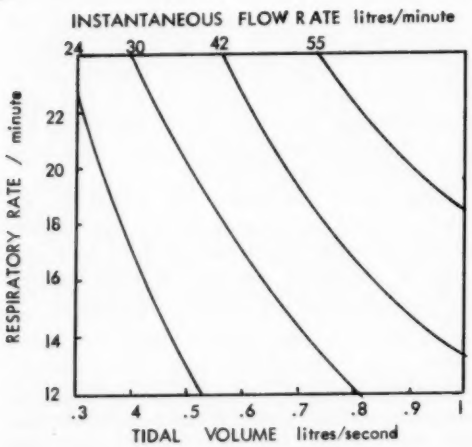

FIG. 1

Maximum tidal volume delivered to the patient's lungs with the inspiratory phase one second is limited by the instantaneous flow rate developed at the external end of the endotracheal tube and by the rate of respiration. When this rate is 16–20/minute the flow rate must be at least 40 litres/minute to satisfy the range of TV desired (400–700 ml) and an effective minute volume (alveolar ventilation) of 4–6 litres. The provision of these requirements can be ensured most easily if nondistensible ducts are employed between the gas machine and the patient.

(c) *Pressure amplitude* is the most difficult parameter to determine because the anaesthetist must guess at the mechanical properties of the lung (Anschütz et al., 1955; Dobkin et al., 1956 a, b). The data which follow can assist in deciding upon a satisfactory pressure pattern.

In the awake, normal, erect subject the compliance of the lung is usually greater than 100 ml/mm Hg, so that about 120 ml of air can enter the lungs per second for each mm Hg negative intrathoracic pressure during the inspiration. The amount of air entering the lungs decreases to about 100 ml air/mm Hg when the supine position is assumed, and is even less in abnormal postures. These air flows hold true when the resistance in the subject's airway is about 1–3 mm Hg in the erect and 2–5 mm Hg in the supine position. Therefore it is necessary to apply in the fully relaxed (curarized) subject approximately 8 mm Hg positive pressure to deliver 500 ml air to the lungs in 1 second when the subject is supine, and at least 10 mm Hg positive pressure when abnormal postures are assumed, if the flow rate is at least 30 l./min (Spalding, 1955).

When a normal patient is anaesthetized, and fully relaxed, the compliance of his lungs decreases to 60–80 ml/mm Hg, the anaesthetic circuit usually adds resistance of 1–2 mm Hg/l./sec, and the anaesthetic gases and vapours (except ethylene-oxygen) add slight resistance due to the greater density than air. If this patient has bronchitis, asthma or emphysema, or if he is placed in an abnormal position (prone, lateral flexed, Trendelenburg, etc.) compliance decreases and resistance of the lungs increases more. Both are altered still more if pulmonary oedema is present. When surgical pneumothorax is produced, the resistance alone may be greatly increased (Marshall and Dubois, 1956; Attinger et al., 1956; McIlroy and Marshall, 1956; Brownlee and Allbritten, 1956; Butler and Smith, 1957; Campbell et al., 1957; Sharp et al., 1958; v. fig. 2).

It follows from the foregoing that the application of a peak pressure of 15 mm Hg during the inspiratory phase of the cycle will be necessary in most clinical conditions to deliver, in 1 second, tidal volumes in the range of 400 to 700 ml. This pressure should not be exceeded in the presence of excessive degrees of resistance, for at this level an increase in pressure produces a small increase in the tidal volume (Spalding, 1955). The alternative and most efficacious treatment in this situation is to reduce secretions and maintain a dry tracheobronchial tree with full therapeutic doses of atropine and tracheal suctioning as required; and prevent the excessive bronchomotor tone which accompanies severe bronchitis, asthma and emphysema, with isoprenaline (0.2 mg) by intravenous injection or into the trachea (Dobkin et al., 1956 a, b).

It is helpful to initiate expiration with a subatmospheric pressure of approximately 2 mm Hg

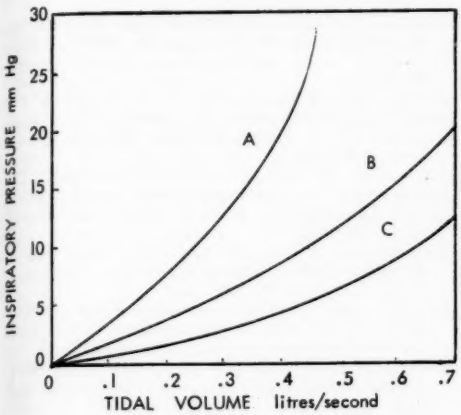

FIG. 2

The delivery of a predicted tidal volume depends also upon the peak pressure developed during inspiration. To deliver an adequate tidal volume to a patient with obstructive breathing due to asthma or bronchitis (curve A) is difficult during anaesthesia even with 15 mm Hg peak pressure, unless bronchodilator drugs are used. During light anaesthesia (curve B) less gas can be delivered to the lungs than during deep anaesthesia (curve C) for an equal peak pressure, respiratory rate and instantaneous flow rate.

during the first half of this phase of the respiratory cycle in order to assist the removal of the alveolar gas. If employed, the negative phase should be less than half the duration of the expiratory phase (0.4 to 1 second).

The anaesthetist should remember that a negative pressure phase does not provide significant benefit to the circulation and ventilation when the chest is opened. Its main advantage depends upon the provision of a low mean airway pressure. This is most important in non-thoracic operations in which support of the venous return to the heart may be necessary (Mørch and Benson, 1954).

COMMENTS

The sole purpose of an anaesthetic is to enable the surgeon to perform his operation with the greatest facility to himself and the greatest advantage to the patient (Mushin, 1957). The general precepts of safe anaesthesia have been clearly outlined by the conscientious teacher (Gilbert, 1952; Cullen, 1954; Eckenhoff, 1956). Just as every physician performs a physical examination of his patient and obtains special information about the blood and the urine, which are important to the evaluation, diagnosis and treatment, so the anaesthetist should procure special information whenever anaesthesia for a major or prolonged operation is necessary—especially in the patient with obstructive signs in the airway, or when there are clinical indications of inefficient myocardial and pulmonary function. In particular, for the patient who will need controlled respiration, and when the use of automatic P.N.P. ventilation is desirable, myocardial function should be estimated clinically and by the response to exercise (e.g., the two step test), supplemented by an electrocardiogram. Pulmonary function also should be estimated as simply and reliably as possible. Any patient who cannot hold his breath for more than 15 seconds (modified Sebrasez test), who cannot exhale the greater part of his vital capacity in 3 seconds, or who has wheezing sounds during expiration should have a fluoroscopic examination and a roentgenogram of the chest during inspiration and expiration (Symposium, 1950). These will reveal the presence of "check valves" and trapping of air during forced expiration. This data may be supplemented by obtaining a timed tracing of the expiration (expirogram) (Dayman, 1951, 1956). The latter can be done on any metabolism machine or rapid recording spirometer. Such data, together with the age, height and "normal" weight of the patient, assist the anaesthetist in selecting the correct rate, tidal volume and pressure amplitude which would be required to provide optimum pulmonary ventilation and maintain cardiovascular homeostasis during anaesthesia. These help to provide fulfilment of the prime role of the anaesthetist, and indicate clearly why any patient under general anaesthesia requires greater ventilation to maintain the physiological state than one who is awake and breathing spontaneously (Scurr, 1956).

Every anaesthetist who has employed fixed pressure or fixed volume ventilators is aware that more pressure is required to inflate the lungs during light than during deep anaesthesia; during intrathoracic than during abdominal operations; when the patient is in abnormal postures than when in the supine horizontal or head elevated position; and when the patient is very obese than

when he is lean. The reasons for these effects are evident, and the underlying causes for some of these have now been described.

Those who wish to depend upon subatmospheric pressure during the expiratory phase to improve pulmonary ventilation and the venous return to the heart should be aware of the "check valve" mechanism, especially in the patient known to be suffering from severe asthma and emphysema (Prinzmetal and Kountz, 1935; Dayman, 1951; Lister, 1958). The resulting effect—trapping of air in the lungs—has been observed clinically when the chest is open in patients with pulmonary tuberculosis, but it is easily overlooked in nonthoracic operations (Dobkin et al., 1956 a, b). When overlooked the "check valve" mechanism may play a part in reducing intrapulmonary airflow to a point where it may virtually cease, and myocardial function may be so severely compromised by the sudden sustained rise of intrapulmonary pressure that the blood pressure may disappear. It is wise, therefore, to assign the subatmospheric pressure phase to the initial part of the expiratory phase of the respiratory cycle, to limit its pressure to less than 5 mm Hg, and to be sure that it is used only in the presence of a dry, fully relaxed tracheobronchial tree.

SUMMARY

Recent data on anaesthetic circuits and on the mechanics of pulmonary ventilation have been applied to clinical anaesthesia. The rules deduced from these data have been found to prevent an otherwise safe anaesthetic from being converted to one which is hazardous. During controlled respiration these rules involve selective employment of each anaesthetic circuit, the provision of adequate gas flows, and careful choosing, packing and regulating the use of carbon dioxide absorbents. They also require individual and critical selection of the tidal volume, the rate of breathing and the pressure amplitude according to the size of the patient, the condition of his heart and lungs, and the assumed posture which is necessary to facilitate the operation.

REFERENCES

Anschütz, F., Duebel, B., Drube, H. C., and Seusing, J. (1955). Uber die Bedeutung des intrapulmonalen Druckes bie der endotrachealen Beatmung. *Der Anaesthesist*, **4**, 72.

Attinger, E. O., Monroe, R. G., and Segal, M. S. (1956). The mechanics of breathing in different body positions. I: In normal subjects. *J. clin. Invest.*, **35**, 904.

—— Herschfus, J. A., and Segal, M. S. (1956). The mechanics of breathing in different body positions. II: In cardiopulmonary disease. *J. clin. Invest.*, **35**, 912.

Brownlee, W. E., and Allbritten, F. F. (1956). The significance of the lung-thorax compliance in ventilation during thoracic surgery. *J. thorac. Surg.*, **32**, 474.

Butler, J., and Arnott, W. M. (1955). The work of pulmonary ventilation at different respiratory levels. *Clin. Sci.*, **14**, 703.

—— Smith, B. H. (1957). Pressure-volume relationships of the chest in the completely relaxed anaesthetized patient. *Clin. Sci.*, **16**, 125.

Campbell, E. J. M., Martin, H. B., and Riley, R. L. (1957). Mechanisms of airway obstruction. *Bull. Johns Hopk. Hosp.*, **101**, 329.

Christie, R. V. (1934). The elastic properties of the emphysematous lung and its clinical significance. *J. clin. Invest.*, **13**, 295.

Cournand, A., Motley, H. L., Wërko, L., and Richards, D. W. (1948). Physiological studies of effects of intermittent positive pressure on cardiac output in man. *Amer. J. Physiol.*, **152**, 162.

Cullen, S. C. (1954). *Anaesthesia in General Practice*, 4th ed. Chicago: Yearbook Publishers Inc.

Dayman, H. (1951). Mechanics of airflow in health and in emphysema. *J. clin. Invest.*, **30**, 1175.

—— (1956). Clinical equivalents of pulmonary function tests. *N.Y. St. J. Med.*, **56**, 2813.

Dobkin, A. B. (1958). Clinical and laboratory evaluation of a pulmonary ventilator with volume control and pressure indicator. *Canad. Anaesth. Soc. J.* (in press).

—— Hubay, C. A., Mendelsohn, H. J., and Hingson, R. A. (1956a). Anaesthesia with controlled positive and negative pressure respiration. Part I: A clinical evaluation. *Brit. J. Anaesth.*, **28**, 296.

—— Wyant, G. M. (1956b). Anaesthesia with controlled positive and negative pressure respiration. Part II: Review of cardiorespiratory function and acid-base homeostasis. *Brit. J. Anaesth.*, **28**, 353.

Eckenhoff, J. E. (1956). Some preoperative warnings of potential operating-room deaths. *New Engl. J. Med.*, **255**, 1075.

Fry, D. L., Ebert, R. V., Stead, W. W., and Brown, C. C. (1954). The mechanics of pulmonary ventilation in normal subjects and patients with emphysema. *Amer. J. Med.*, **16**, 80.

Gilbert, R. G. B. (1952). Safer anaesthesia. *Canad. med. Ass. J.*, **66**, 267.

Gordon, A. S., Frye, C. W., and Langston, H. T. (1956). The cardiorespiratory dynamics of controlled respiration in the open and closed chest. *J. thorac. Surg.*, **32**, 431.

Hunt, K. H. (1955). Resistance in respiratory valves and canisters. *Anesthesiology*, **16**, 190.

Lister, W. A. (1958). The check valve mechanism and the meaning of emphysema. *Lancet*, **1**, 66.

Mapleson, W. W. (1954). The elimination of rebreathing in various semi-closed anaesthetic systems. *Brit. J. Anaesth.*, **26**, 323.

Marshall, R., and Dubois, A. B. (1956). The viscous resistance of lung tissue in patients with pulmonary disease. *Clin. Sci.*, **15**, 473.

McIlroy, M. B., and Christie, R. V. (1954). The work of breathing in emphysema. *Clin. Sci.*, **13**, 147.

—— Marshall, R. (1956). The mechanical properties of the lungs in asthma. *Clin. Sci.*, **15**, 345.

—— —— Christie, R. V. (1954). The work of breathing in normal subjects. *Clin. Sci.*, **13**, 127.

Mead, J., and Whittenberger, J. L. (1953). Physical properties of human lungs measured during spontaneous respiration. *J. appl. Physiol.*, **5**, 779.

—— Lindgren, I., and Gaensler, E. A. (1955). The mechanical properties of the lungs in emphysema. *J. clin. Invest.*, **34**, 1005.

Mørch, E. T., and Benson, D. W. (1954). Automatic artificial respiration during anaesthesia. *Proc. 3rd Congress scand. soc. Anaesth.*, p. 30.

Mushin, W. W. (1957). Advances in anaesthesia: real or apparent. *N.Y. St. J. Med.*, **57**, 3279.

Orkin, L. R., Siegel, M., and Rovenstine, E. A. (1954). Resistance to breathing by apparatus used in anesthesia. I: Endotracheal equipment. *Curr. Res. Anesth.*, **33**, 217.

—— —— —— (1957). Resistance to breathing by apparatus used in anesthesia. II: Valves and machines. *Curr. Res. Anesth.*, **36(2)**, 19.

Otis, A. B., Fenn, W. O., and Rahn, H. (1950). Mechanics of breathing in man. *J. appl. Physiol.*, **2**, 592.

Prinzmetal, M., and Kountz, W. B. (1935). Intrapleural pressure in health and disease and its influence on body function. *Medicine*, **14**, 457.

Radford, E. P., jr., Ferris, B. G., jr., and Kriete, B. C. (1954). Clinical use of a nomogram to estimate proper ventilation during artificial respiration. *New Engl. J. Med.*, **251**, 377.

Scurr, C. F. (1956). Controlled respiration: standardization of ventilation. *Brit. J. Anaesth.*, **28**, 23.

Sharp, J. T., Griffith, G. T., Bunnell, I. L., and Green, D. G. (1958). Ventilatory mechanics in pulmonary edema in man. *J. clin. Invest.*, **37**, 111.

Spalding, J. M. K. (1955). Pressure and duration of inspiration during artificial respiration by intermittent positive pressure. *Lancet*, **1**, 1099.

Symposium: Report of the sub-committee on pulmonary function tests. American Trudeau Society (1950). *Amer. Rev. Tuberc.*, **62**, 451.

Woolmer, R., and Lind, B. (1954). Rebreathing with a semiclosed system. *Brit. J. Anaesth.*, **26**, 316.

ON CHLOROFORM AND OTHER ANÆSTHETICS

THEIR ACTION AND ADMINISTRATION

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Licentiate of the Royal College of Physicians

(*Continued from page* 252)

Raising depressed Portions of Skull. In Dec. 1848, I administered chloroform to a gentleman in Norfolk, aged sixty-two, on whom the late Mr. Aston Key operated. The patient had been thrown from his horse four years previously, and probably kicked whilst on the ground. He believed that he did not lose his consciousness. There was a considerable depression of a portion of the right parietal bone, near its upper and posterior angle; but there were no symptoms of cerebral pressure or irritation for two years after the accident; but at that time he fell from his seat in some kind of fit, after which he had partial paralysis of the left arm, impaired vision, and a melancholy or apathetic state of mind. He was also subject to attacks of real or apparent suspension of breathing, and to occasional attacks of vomiting.

His ordinary medical attendant, Dr. Bell of Aylsham, objected to the chloroform, on account of feeble and irregular action of the heart, in addition to the above symptoms. The patient, however, became gradually insensible, without any unfavourable symptoms. After making incisions in the scalp, Mr. Key sawed out a good sized piece of the parietal bone with Hey's saw. The insensibility was kept up gently during the operation, which lasted above half an hour. There was pus under the bone, and the dura mater was diseased, and gave way during the operation. Mr. Key immediately expressed a bad opinion of the case. The patient recovered his consciousness in about a quarter of an hour, and in a little time was in the perfect enjoyment of all his faculties, being very cheerful, and in a totally different state from the one of apathy and almost unconsciousnes, in which he appeared when we first saw him. He was attacked with inflammation of the brain on the third day, and died on the fifth.

In May 1855, I administered chloroform in St. George's Hospital to a young man who had been kicked by a horse. The frontal bone above the right eye was driven in to a good depth, and a little of the brain had escaped. Mr. Cæsar Hawkins cut a piece from the frontal bone, just above the depressed portion, with the bone forceps, to enable him to introduce the elevator. The depressed portion being quite loose, was removed, together with the roof of the orbit. The youth was partially comatose before chloroform was given, but made a resistance to the operation. A week after the operation, when I saw him, he was conscious, but feverish, and he died a week or two later.

Mr. Bowman, on one occasion, made an incision over the frontal sinus in a gentleman; and made an aperture in the outer table of the frontal bone, which gave exit

to a quantity of pus which had been formed in the sinus.

In the summer of 1847 the late Mr. Liston performed a similar operation on a lady, the patient of Dr. Locock, who was present. I exhibited sulphuric ether on that occasion.

Operations for ununited Fracture. I have notes of seven operations by Mr. Fergusson and Mr. Bowman, for ununited fracture of the femur, humerus, radius, and ulna. The usual course has been to scrape and puncture the ends of the bones by subcutaneous incision, and where this has not succeeded, to cut down on the bones and saw off the ends; or to bore holes near the ends, and introduce ivory pegs.

The Reduction of Dislocations. I have notes of twenty-seven cases in which I have administered chloroform during the reduction, or attempted reduction, of dislocations. Only three of these were recent dislocations. One had existed a few days; and the other twenty-three for some weeks or months. Twelve of the operations were performed by Mr. Fergusson, and the others by Mr. Cæsar Hawkins, Mr. Cutler, Mr. Bransby Cooper, Mr. Partridge, Mr. Tatum, Mr. H. C. Johnson, Mr. Charles Hawkins, Mr. Hewett, Mr. Henry Lee, and Mr. Price. Most of the dislocations at the shoulder were quite successfully reduced; one of them by the late Mr. Bransby Cooper, as long as ten weeks after the accident. Dislocations of the hip were successfully reduced in three weeks and five weeks after the accident. At longer periods, dislocations of the femur were often benefited by the operation, but not completely reduced. The dislocations at the elbow were not successfully reduced except when recent, although the position and motion of the forearm were improved in several cases by the operation. Pulleys were applied, often for a length of time, in the old dislocations; and many even of the successful operations could not have been performed except the patient had been in a state of anæsthesia. A full dose of chloroform is required in the attempts to reduce old standing dislocations, in order to suspend, as nearly as may be, the resistance of the muscles.

Forcible Movement of Stiff Joints. I have given chloroform in twenty-two operations of this kind, within the last three years, for the restoration of motion in the knee, elbow, and hip, after the joints had become fixed in one position, generally by adhesions resulting from disease. The first operation of the kind in which I assisted was one performed by Mr. Brodhurst, whom I have since assisted more frequently in these kind of operations than any other surgeon; but other operations have been performed by Mr. Fergusson, Mr. Cæsar Hawkins, Mr. Partridge, Mr. Bowman, Mr. Hewett, and Mr. Edwin Canton. These operations would evidently not have been performed except for the discovery of producing a state of anæsthesia by inhalation.

Tenotomy. I have memoranda of 78 cases of tenotomy in which I have administered chloroform. In some of the cases which have occurred during the last two or three years, forcible movement of a stiff joint has been resorted to, in addition to the tenotomy. I applied chloroform in St. George's Hospital in tenotomy, when the agent was first intro-

duced; and have also given it in King's College Hospital for ten years. During these ten years, I have also administered chloroform to a number of the private patients of Mr. Fergusson, whilst he has performed tenotomy, and to those of other surgeons occasionally. During the last three years, I have given it in several operations by Mr. William Adams. I understand that several orthopædic surgeons had, at one time, an objection to chloroform in tenotomy, from an impression that it would relax the muscles, and thus render the operation less easy of performance. But it is altogether unnecessary to carry the effects of chloroform so far as to relax the muscles. The pain of this operation can always be prevented without relaxing the muscles, which are indeed often more tense than if the patient were awake.

Operations for Strangulated Hernia. I have notes of only nineteen cases of operations for strangulated hernia in which I have administered chloroform since the end of 1849. This operation is, I believe, often performed without the use of this agent. Fifteen of the cases in which I have exhibited chloroform were inguinal or femoral hernia, and four cases were umbilical hernia. In these latter cases, the patients all died.

In one of the cases, there was a complication, in addition to the hernia. The patient was an old gentleman, and the surgeon had directed him to apply ice and salt, and had either given no directions respecting the time it was to be applied, or the directions were misunderstood. The patient was a scientific man, and applied the ice and salt most effectually for about four hours. When we arrived, a portion of the integuments around the umbilicus, larger than the palm of the hand, was as hard as a board, and of a dull white colour. The surgeon said that he could not turn back the flaps of the integument, if he made them whilst it was in that hardened state. The part thawed whilst the patient was inhaling chloroform, and when the incisions were made some fluid blood of a light crimson colour flowed. Iced water was applied to the part immediately after the operation, for a short time. The integuments which had been frozen sloughed two days after the operation. The patient had peritonitis, and died on the fifth day.

On March 6th, 1848, a man was placed on the operating table in St. George's Hospital, with a strangulated femoral hernia. I administered chloroform to him at the request of Mr. H. C. Johnson; and when he became completely insensible and the muscular system relaxed, Mr. Johnson readily reduced the hernia by means of the taxis, although it was previously quite incapable of reduction. If the taxis had not been successful, the operation, for which the instruments were arranged ready, would at once have been performed whilst the patient was insensible. I do not think that chloroform has been sufficiently employed of late years during the application of the taxis to strangulated hernia.

In every case in which sickness was present, it was relieved by the chloroform. And vomiting returned in scarcely any instance, after the chloroform, so long as I remained in the room.

Operations for Hæmorrhoids and Prolapsus Ani. I have memoranda of 171

operations for these affections in which I have administered chloroform. A great number of these operations have been performed by Mr. Fergusson and Mr. Salmon; but I have also assisted Mr. Cæsar Hawkins, Mr. Bowman, Mr. Quain, Mr. Erichsen, and a number of other surgeons, whilst performing this operation. The patient always lies on one or the other side during this operation, with the knees drawn up towards the stomach. The chloroform should be inhaled till the patient is quite insensible, that is, till the edge of the eyelid can be touched without causing winking, otherwise he is apt to stretch out his legs, as soon as the operation is commenced. Ligatures always, or nearly always, introduced with a needle, have been applied to the mucous membrane in every case both of hæmorrhoids and prolapsus ani, except in two or three in which Mr. Henry Lee applied nitric acid and the actual cautery. In a great number of the cases, however, folds of redundant and diseased skin were cut away from around the anus, with a pair of large curved scissors, after the ligatures had been applied to the mucous membrane. It is the rule in these cases never to cut the mucous membrane, and never to tie the skin. It is desirable to get the patient to protrude the hæmorrhoids by bearing down at the night stool before he inhales the chloroform; and they always remain protruded during the operation; indeed, there is generally a good deal of bearing down during the operation under chloroform, and if the bowels have not been entirely emptied, they are apt to act as the operation is being performed. It is customary, and very desirable, to give a full dose of opium almost as soon as the patient wakes from the chloroform, to diminish the pain caused by the ligatures. I have, in a few cases, continued to administer the chloroform at intervals for an hour or two after the operation, till the opium began to take effect; and I consider that it would be useful, in some cases, to give the opiate two or three hours before the operation. I administered chloroform to two ladies, one a patient of Mr. Bowman, and the other of Mr. Wm. Adams, whilst hæmorrhoids were removed by the écraseur. The operations lasted rather more than half an hour; but the chloroform, after the commencement of the operation, required only to be kept up to a moderate extent. There was no hæmorrhage in either case; and it seemed to me that the great pain which is caused by the presence of the ligatures would be prevented by this means of operating.

Hæmorrhoids and prolapsus ani are peculiarly prevalent in the upper class of society. That small portion of English people who dine in the evening seem to furnish more cases of hæmorrhoids for operation than all the rest of the population. And I am inclined to attribute the circumstance to the habit of taking the greater part of the food towards the close of the day, after a long fast; by which means congestion of the liver, and obstruction to the return of blood from the bowels is induced. Many of the patients with hæmorrhoids are ladies who are far from luxurious in their habits, indeed many of them are abstemious; and many of the male patients are the reverse of sedentary, as they spend a great part of their time in hunting, and other field sports. Again, the

complaint cannot in my opinion be attributed to highly seasoned food, as I think the working classes use more pepper than fashionable people. I am inclined to believe that the habit of taking the chief meal of the day at twelve or one o'clock, is the principal reason why bad cases of hæmorrhoids are comparatively so rare in the working and middle classes, many of whom live luxuriously, and are more sedentary in their habits than the higher class of society.

Several of the patients operated on for hæmorrhoids were extremely blanched, from the continued loss of blood arising from the disease; but these patients underwent both the action of the chloroform and the operation very well. The operation, it must be remembered, is not attended with loss of blood.

Fissure of the Anus. I have notes of forty-four cases in which I have exhibited chloroform in operations for the cure of this disease. Two of them were performed by the late Mr. Copeland. The sphincter ani was divided in the greater number of the operations. In addition to these cases, there were some in which fissure existed, along with hæmorrhoids, or fistula *in ano*. The patient was always placed on his side, in the same position as in the operation for hæmorrhoids.

Operations for Fistula in Ano. The position of the patient in this operation should be the same as in those for hæmorrhoids and fissure of the anus, unless the patient is placed on the back, in the lithotomy position, as I have seen in a few cases.

I have memoranda of 218 cases in which I have given chloroform in operations for fistula *in ano*. In many of the cases the sinuses were very numerous and extensive. It is necessary that the patient should be quite insensible during this operation, to prevent the possibility of his moving suddenly whilst the bistoury is being used.

Operations on Ovarian Tumours. I have notes of three cases in which I gave chloroform during the removal of an ovarian cyst. The first of these was in March 1850. Twenty-four pints of liquid were first evacuated from the tumour. It consisted of four cysts united together, two of which contained serous fluid of slightly different colour; the third contained serum tinged with blood, and the fourth and smallest cyst, a purulent fluid. An incision was made, twelve or fourteen inches in length, extending from the pubes to midway between the umbilicus and sternum. Some slender adhesions were removed at one spot. The tumour was attached by a membranous pedicle, with the left iliac fossa, and the fundus of the uterus. Needles were passed through the pedicle, and it was tied in three or four portions, when the tumour was removed. After the tumour was removed, the patient seemed to breathe entirely by the ribs, the diaphragm remaining relaxed, and not contracting, whilst the wound in the abdomen was being closed. Scarcely any blood was lost during the operation. The patient died of peritonitis early on the fourth day.

The next case occurred on August 27th, 1850, and is reported in the *Medico-Chirurgical Transactions* for 1851. Mr. Duffin was the operator, and the patient made a favourable recovery.

The third operation was performed on the 31st of January, 1854. The patient

was a spinster, twenty-eight years of age, and the tumour had not been tapped. It contained about two gallons of clear fluid, and was removed through an opening in the median line above the umbilicus, about seven inches in length. There was no depression when the patient awoke after the operation. She died within three days.

I administered chloroform in two cases where it was intended to remove an ovarian cyst. In one case the cyst was so adherent to the peritoneum that it could not be removed; in the other case, there was no cyst, but some serum in the peritoneal cavity, and a tumour growing from the fundus of the uterus. This tumour was allowed to remain. Several medical men, in addition to the operator, had diagnosed an ovarian tumour in this case. These two patients recovered.

I exhibited chloroform in four operations in which an ovarian cyst was opened, and the cut edges of it sewed to the wound in the abdominal parietes. These four patients, I believe, all died. I am quite certain as regards three of them.

On March 10th, 1852, I administered chloroform in St. Mary's Hospital to a woman, apparently about thirty-five, who had suffered from an ovarian cyst about eighteen years. Mr. Isaac Baker Brown made an incision, about six inches in length, into the peritoneal cavity, drew out a portion of the cyst, tapped it, and removed several pints of clear serum. He then cut away a piece of the anterior wall of the cyst, about as large as the hand, and allowed the rest of the cyst to remain loose in the abdomen. The wound in the parietes of the abdomen was stitched up. If I remember rightly, the patient died, but I have no note of the result.

Operations for Cancer of the Vagina. I have notes of eighteen cases in which I have given chloroform for operations of this kind by the knife, which would have been extremely painful without the use of an anæsthetic.

I exhibited this agent, in 1848, to a lady, whilst the late Mr. Aston Key applied the actual cautery to malignant excrescence of the os uteri; and I have administered it in several cases in which potassa and other caustics have been applied to the os uteri. In operations on the vagina or perineum, the woman should inhale the chloroform whilst lying on her back; and when insensible, should be drawn to the edge of the bed, or the foot of the operating table, and have the knees held back and separated.

Operations for Rupture of the Perineum. I have notes of fourteen operations for this accident Six of them were performed by Mr. I. B. Brown, five by Mr. Fergusson, and the others by Mr. Paget, Dr. Protheroe Smith, and Mr. Henry Lee. Mr. Fergusson has, in five cases, performed an operation for prolapsus uteri, by paring the edges of the outlet of the vagina, and stitching them together so as to diminish the orifice.

I have given chloroform in several operations for vesico-vaginal fistula, some of which were performed by Mr. Spencer Wells; and also for the removal of warts and other growths from the labia pudendi, either by the knife or caustics.

Removal of the Testicle; Amputation of the Penis, etc. I have memoranda of twenty-seven cases in which I have administered chloroform during the

removal of a testicle, generally for malignant disease; and six cases in which I have administered it for amputation of the penis, always for malignant disease. There were six operations, also, in which a part of the penis was removed for malignant disease; and eleven cases in which warts were removed from the glans penis, generally with the knife. In two cases in August 1854, Mr. Acton destroyed a number of venereal warts on the glans penis and prepuce by a caustic composed of potassa and lime. In all the operations on the testicle and penis, under chloroform, the patients have been lying on the back.

Operations for Phymosis. I have memoranda of 76 operations for phymosis, in which I have exhibited chloroform. The operations were generally in the adult, although the complaint was, in most cases, congenital. I have known two cases in which cancer of the penis was produced by the patient's suffering a congenital phymosis to remain to about the age of fifty. The cancer commenced in the glans from the irritation of the retained urine. One of the patients died of the disease.

Removal of enlarged Bursa. I have notes of six cases in which the bursa of the patella was dissected out by the surgeons of King's College Hospital for housemaid's knee. The patients were charwomen and domestic servants. In two cases a bursa was removed from the forefinger.

Evulsion of the Nails. I have notes of twenty-five cases in which I have given chloroform for cutting down the nail of the great toe, and tearing away the whole, or the two edges of it; and also of three cases in which one or more finger-nails were removed by a similar process. This operation is one of the most painful of the minor operations of surgery. It is better that the patient should be lying when it is done under chloroform.

Laryngotomy. I administered chloroform to one or two infants in which Mr. Henry Smith performed laryngotomy for croup. I also administered it, on four occasions, to a patient of Mr. Partridge, a boy four years old, who was believed to have a button in some part of the air-passages. The larynx had been opened a few days previously to the first occasion in which I gave chloroform, and I administered it on a sponge held near to the tube in the larynx. It was necessary to give the vapour gently at first, just as if it was entering in the usual way. When it was given at all strong, whilst the patient was still conscious, he showed exactly the distress that a patient experiences when he says that the vapour produces a choking feeling; which confirms my opinion that the feeling referred to the throat, from the action of pungent vapours and gases, is caused by their presence in the lungs. The chloroform was given to keep the child quiet whilst Mr. Partridge searched for the supposed button in the larynx and bronchi. When the child recovered from the chloroform, before the operation was concluded, the explorations in its air-passages embarrassed the breathing much more, and caused more apparent threatening of suffocation, than they did when he was under the influence of the vapour. This little boy remained for months in King's College Hospital; and at last the embarrassment in his breathing

subsided, and the tube was removed from the larynx, and the wound allowed to heal; and he left quite well, although the button, which was supposed to have gone down his windpipe at the moment when his symptoms first suddenly came on, was never found.

I have administered chloroform in a great variety of surgical operations, in addition to those mentioned above, but as they required only the usual management in the application of the vapour, I need not allude to them, but shall, however, make a few remarks regarding dental operations.

Extraction of Teeth. It is the custom in the medical journals and medical societies, to object occasionally to the use of chloroform in tooth-drawing, as if the operation were not sufficiently severe to require it. I will say nothing of the wives and daughters of medical men in connexion with this subject, but will only allude to the case of an elderly lady, who had for thirty years been the private friend, as well as the patient, of one of the Council of the College of Surgeons. After she had had ten necrosed teeth extracted, and had awakened from the effects of the chloroform, her friend and surgeon, who had been looking on, discoursed eloquently on her case, explaining how the state of her mouth was ruining her health; how impossible it would have been for her to go through the operation without chloroform, and what a great advantage it was.

Dr. Watson says in his lectures: *"I am not at all sure that the increased longevity of modern generations is not, in some degree, attributable to the capability of chewing their food which the skill of the dentist prolongs to persons far advanced in life." I have seen at least fifty cases in which the dentist has been able to exert his skill in enabling his patient to masticate only by the aid of chloroform; cases of feeble, aged, or debilitated persons, whose mouths contained between twenty and thirty stumps of teeth or necrosed teeth; and who were able to get rid of them all at two or three operations a few days apart; but without the opportunity of being made insensible, would undoubtedly have continued with the mouth in a tender and painful state.

It was in consequence of the relief afforded by nitrous oxide gas, in pain caused by a tooth, that Sir Humphrey Davy suggested its application in surgical operations; it was for the extraction of a tooth that Mr. Horace Wells first carried out the suggestion of Davy; and it was in the extraction of teeth that Dr. Morton first employed sulphuric ether as a substitute for nitrous oxide gas. These circumstances seem to point to a demand for anæsthetics in operations on the teeth; and when the great frequency of these operations is considered, it is probable that more pain may be prevented during their performance than in any other class of operations.

I have notes of 867 cases in which I have administered chloroform during the the extraction of teeth, chiefly by dentists living in this neighbourhood: amongst whom are Mr. Saunders, Mr. Cartwright, Mr. Samuel Cartwright, Mr. Arnold Rogers, Mr. Thomas A. Rogers, Mr. Tomes, Mr. Bigg, Mr. **Crampten, Mr.**

* Fourth edit., vol. ii, p. 467.

F. W. Rogers, Mr. Alfred Canton, Mr. Woodhouse, Mr. Lintott, Mr. Rahn, Mr. Vasey, Mr. Sercombe, Mr. Fletcher, and several others; and there is one dentist in the City, Mr. West of Broad Street, whom I have frequently assisted. The number of teeth, or stumps of teeth, extracted in these 867 operations, has been about 3021. In some cases in which several teeth have been removed, I have not been sure of the exact number, but have put down about the number.

The number of teeth extracted at an operation has varied from one to nineteen. The latter number was extracted by Mr. Canton on one occasion, and on two or three occasions Mr. Arnold Rogers and Mr. Samuel Cartwright extracted seventeen at one sitting; but these gentlemen and others, as well as myself, have thought it better, as a general rule, to make more than one operation, when the number of teeth to be drawn exceeded ten, in order that the mouth might not contain too many wounds at one time, and that the loss of blood might not be very great. A great number of the operations have been for the extraction of the four first permanent molars, in children about thirteen, as these teeth are very apt to decay at an early period.

I have on 181 occasions, of which I have memoranda, given chloroform for the extraction of a single tooth. I exhibited it lately to a lady, aged eighty-six, whilst Mr. Bigg extracted an abortive wisdom tooth, which had recently come through the gum, and was giving pain. She awoke in about two minutes after the operation, and was quite cheerful and well.

The patients have been seated in an easy chair in all the operations on the teeth, except in a very few cases where a female patient was too ill to sit up. In many cases, and always if there was any feeling of faintness, the patient has been placed on a sofa, after the operation, for twenty minutes or half an hour. I am not aware of any inconvenience from the chloroform, in any of the cases of tooth drawing, excepting sickness and vomiting, which in a very few of the cases have been troublesome for some time.

It is necessary in tooth-drawing to make the patient unconscious and to continue the chloroform a little while after unconsciousness is induced, till the sensibility of the edge of the eyelid is very much diminished, or almost altogether suspended, otherwise the patient will probably make a resistance that will interfere with the operation, or scream out and alarm his or her friends. I nearly always take about four minutes in the inhalation. It is not desirable to take longer than five or six six minutes, as the patient would be slower than is desirable in recovering completely from the effects of the vapour.

The patient is usually in the third degree of narcotism when the operation is performed, and, in this degree, as was previously stated, there is not unfrequently a contracted and rigid state of the muscles. This state often affects the muscles of the jaws, and interferes with the opening of the mouth, if it be closed. I generally tell the patient to keep his mouth open whilst inhaling, and by that means it often remains open when he is insensible. Not unfrequently, however, he closes it on becoming insensible. One can

generally open it by pressing on the chin; but as the chin does not afford a very favourable hold, there are a very few cases in which the mouth cannot be opened easily in this way, at least not unless the effects of the chloroform are carried further than is desirable for these operations. I therefore carry with me a little instrument of two blades, made to open by means of a screw. The ends of the blades are covered with leather, and, if introduced between the teeth, at the corner of the mouth on the side opposite to that on which the dentist is about to operate, the mouth can easily be opened.* The power of the instrument is only such that I can scarcely open it with one hand, when I hold the blades with the other. It would not enable one to open the mouth of an adult if he were closing it by voluntary power; but the spasm caused by chloroform is very much less powerful than the action of the muscles when influenced by the will. I never use the instrument for opening the mouth when the patient is closing it voluntarily under the influence of a disordered consciousness, but always wait till consciousness and volition are entirely suspended. When the mouth is once opened, it can generally be kept open with the fingers, and the instrument may be withdrawn.

The bleeding during tooth-drawing is never so free as to interfere with the breathing; but when more than two or three teeth are extracted, and especially if they be in the back part of the mouth, some of the blood which escapes nearly always flows into the stomach; it flows down the fauces and œsophagus usually without any act of deglutition; but the evidence of its having gone into the stomach is obtained in those cases where the patient vomits. In consequence of the blood flowing into the stomach, vomiting cannot so generally be prevented by the precaution of not taking a meal before the operation in tooth-drawing as in other operations; but the sickness usually subsides as soon as the patient has emptied his stomach.

* It was made by Mr. Mathews, Portugal Street. It was not contrived by me.

(To be continued)

THE EMPHYSEMATOUS PATIENT

Sir,—In Dr. Nunn's article on "The Anaesthetist and the Emphysematous Patient" (*Brit. J. Anaesth.*, 1958, **30**, 134), he suggests that halothane might prove a satisfactory inhalation agent for emphysematous patients.

Certainly, its nonirritant properties and the fact that only low concentrations are needed, even in the presence of a large functional residual capacity, are both attractive features.

However, there appear to be two disadvantages. Firstly, halothane is usually given with a very high percentage of oxygen which thus weakens the "anoxic drive" needed by these patients. Secondly, halothane itself is a respiratory depressant.

If spontaneous respiration is to persist then the oxygen content of the inhaled gases should be reduced by a diluent—and what better one than nitrous oxide.

The calibrated inhaler for Fluothane, manufactured by the British Oxygen Company, gives readings relative only to oxygen flows. The company, however, say that diluting the oxygen flow with nitrous oxide does not influence the calibration of this inhaler. The use of it in this way seems to me to be a sensible procedure for the emphysematous patient. Obviously the nitrous oxide will have a potentiating effect on the strength of the mixture, which must be taken into account.

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TERMINOLOGY AND SYMBOLS USED IN RESPIRATORY PHYSIOLOGY

Sir,—I do not feel very strongly about most of the questions raised by Dr. Mapleson in his letter to the journal (*Brit. J. Anaesth.*, 1958, **30**, 202). I see no reason, for example, why italics should not be used instead of Roman type. On the other hand, the rare and trivial case where an italic *I* is preferable does not make the issue a burning one. Indeed, few people would notice such a change.

The "on the line" subscript does have some advantages when multiple subscripts are used. On the other hand, Dr. Mapleson has pointed out a disadvantage. So far as I know, however, no one has yet mistaken a subscript for a multiplying factor. The use of a dot to represent a time derivative certainly has disadvantages when applied to intermittent processes as pointed out by Dr. Mapleson. His solution to the problem—namely to use a different symbol for intermittent gas flow—seems perfectly justifiable to me. As pointed out in the report of our committee, new symbols are easily added to the list without altering the method of symbolization.

In summary, I do not see that Dr. Mapleson's suggestions would change matters much—the shift to italics would scarcely be noticeable. It is my personal opinion that the present method of presenting subscripts is somewhat simpler to read when multiple subscripts are used, but I would not object violently if this were abandoned. I think all members of our committee were surprised and pleased at the almost universal acceptance and use of the present symbols in so many countries and languages. Many journals have used the symbols during the past eight years.

This is not to say, however, that improvements cannot be made.

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Anaesthesia for Nurses. By Eric Godwin, Consultant Anaesthetist to the Croydon Group of Hospitals. Published by John Wright & Sons Ltd., Bristol.

"Theirs not to reason why, theirs but to do and die" may be a suitable motto for soldiers, though I imagine a little out of date, but it is not good enough for a nurse. To acquire some knowledge of physiology, respiration and circulation, of pharmachology, the drugs used as analgesics anaesthetics and relaxants, is not only for her to find a new interest in life but to make her a most useful assistant to the anaesthetist and an expert in whose hands the semiconscious patient may be safely left. This little book will reinforce her practical experience in the anaesthetic room and theatre, and help to elucidate points that may not have been made clear during the stress of the operation.

E. Falkner Hill

Medical Electrical Equipment. Advisory Editor, Robert E. Molloy. Published by George Newnes Ltd. Pp. 324; illustrated. Price 35*s.*

"This book has been prepared in the belief that there is a real and urgent need for authoritative information on the principles, operation, care and routine maintenance of medical electrical equipment, presented in terms that do not presuppose a deep knowledge of electricity."

These words are from the preface of this volume and will be fully approved by all who are concerned with hospital operating theatres, sterilization, etc. The Editor, an anaesthetist, has managed to cover an enormous ground in his 306 pages. The subjects range from the structure of operating theatre floors to electroencephalography and include descriptions of air conditioning, suction pumps, methods of refrigeration, constant temperature ovens, foot switches, ultra-violet deodorization and sterilization, resuscitation equipment and transducers used in clinical investigations, and in fact there would seem to be no electrical apparatus likely to be used in hospital that is not here described. Even minutiae are included such as mercury switches and descriptions of various types of electric motors. The text is simple to follow by all who know the rudiments of electricity and yet is sufficiently detailed to include circuitry of diathermy apparatus and biological amplifiers.

The book is beautifully produced and very fully illustrated. It is strongly recommended to all those who wish to be well informed on this aspect of hospital management and it would seem an absolute must for operating theatre technicians.

T. Cecil Gray

Inhalation Analgesia in Childbirth. By E. H. Seward and R. Bryce-Smith. Published by Blackwell Scientific Publications, Oxford. Pp. 56; illustrations 11. Price 7*s.* 6*d.*

In their introduction to this small, but admirable book, the authors have done well to emphasize the scrupulous attention to detail which is required from those who supervise obstetric analgesia. This is one of the most important functions of the midwife who makes use of inhalation methods for the relief of the pains of labour, and it cannot be too vigorously stressed.

The book is well written, easy to read, and full of helpful advice. There are one or two criticisms, however; e.g., nitrous oxide is represented on page 11 as possessing little analgesic power, and only producing analgesia by taking the patient close to the stage of loss of consciousness. I would not agree with this statement.

On page 16 it is advised that inhalations should be started twenty to thirty seconds before the contraction is due. This is not long enough. The technique for giving relief in the second stage of labour is best described by saying that the inhalations should take place between the pains, and be continued until the accessory muscles are used for pushing down.

The warning on page 29 about the importance of not allowing trichloroethylene to come into contact with soda lime in an anaesthetic apparatus is

of paramount importance, and in Chapter 8 the emphasis on the cumulative effect of trichloroethylene, as compared with the absence of such in the case of nitrous oxide and air, is very apt.

I fear that the boiling of masks for ten minutes, as described on page 51, would ruin them.

Having noted these points I heartily recommend this practical manual to the attention of all those engaged in analgesia in childbirth, and I feel sure it will prove of great assistance to them in their work.

R. J. Minnitt

The British Encyclopedia of Medical Practice 1957 (2nd edition). Published by Messrs. Butterworth & Co., 88 Kingsway, London, W.C.2. Price £45 10*s*. (or by 50 monthly instalments of £1 and a final one of 15*s*.).

These are volumes that any doctor would be proud to possess. A foreword by Lord Cohen of Birkenhead calls attention to many of the articles which deal with problems that every doctor will sooner or later come across in practice. It is impossible to suppose that he could fail to be helped by this perusal or that his patients would not so benefit. There are extensive bibliographies and references to every article. In the publishers' announcement at the beginning of the Cumulative Supplement directions are given as to how to make the best use of these volumes. Here, then, is a mine of information and how to dig it out. The possession of them is probably the quickest way.

E. Falkner Hill

Physics for the Anaesthetist (2nd edition). By Sir R. R. Macintosh, Professor W. W. Mushin and Dr. H. G. Epstein. Published by Blackwell, Oxford. Pp. 443; illustrated. Price 60*s*.

The return of *Physics for the Anaesthetist* to the shelves of our bookshops is welcome. The authors make a brave attempt to present to the anaesthetist those aspects of physics which are of interest to him. This new volume is much larger than its predecessor, and this is the result of the inclusion of new subjects, rather than of expansion of the old book. In fact, the first edition is reproduced almost in its entirety, the only major change being in the chapter on gas flows. The new material consists of a chapter on the reducing valve and a section on explosions.

The chapter on the reducing valve might be thought excessively long. As regards its physical principles it is a simple component which in these days of rapidly expanding curriculum should not require thirty-five pages of text for its description.

The section on explosions covers the physicochemical aspects of combustion in some detail. This section, however, lacks the clarity of description which is such a refreshing feature of the older parts of the book. This is perhaps most prominent in the account of electrostatics, where the approach is not one from the first principles.

A remarkable omission from a book on physics for anaesthetists is the lack of any reference to the relationships between the tensions of a spherical membrane and the pressure difference between its two sides. It is upon such tension that the negative pressure within the chest depends, as does the pressure produced by manual compression of rebreathing bags. A brief account of the physical principles involved would not have been inappropriate.

Those of us responsible for the teaching of physics to trainee anaesthetists will have been struck by the wide variations in the knowledge of basic physics possessed by our students. Some are remarkably well equipped, requiring only a rapid revision, whilst others must be taught the subject from very first principles. It is particularly to these latter that this book will appeal. To their teachers it is of great value in assisting them in presenting their subject in a form which is readily assimilable.

The authors have set themselves a difficult task, for they have to present limited aspects of a subject which is virtually without limits. Their choice of what to include and what to exclude must inevitably be to some extent arbitrary, and the authors are to be congratulated on having produced what all will regard as a well-balanced work.

The production of this book is of that high standard which we have come to expect from Messrs. Blackwell Scientific Publications Ltd., and it will prove invaluable to the practising anaesthetist, to the trainee and to teachers. We wish it well.

G. Jackson Rees

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